Safety Regulation Group

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Helicopter Tail Rotor Failures

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List of Effective Pages

Section	Page	Date	Section	Page	Date
Section 6	19	November 2003	Section 7	6	November 2003
Section 6	20	November 2003	Section 7	7	November 2003
Section 6	21	November 2003	Section 8	1	November 2003
Section 6	22	November 2003	Section 8	2	November 2003
Section 6	23	November 2003	Section 8	3	November 2003
Section 6	24	November 2003	Section 8	4	November 2003
Section 6	25	November 2003	Section 8	5	November 2003
Section 6	26	November 2003	Section 8	6	November 2003
Section 6	27	November 2003	Section 8	7	November 2003
Section 6	28	November 2003	Section 8	8	November 2003
Section 6	29	November 2003	Section 8	9	November 2003
Section 6	30	November 2003	Section 8	10	November 2003
Section 6	31	November 2003	Section 8	11	November 2003
Section 6	32	November 2003	Section 8	12	November 2003
Section 6	33	November 2003	Section 9	1	November 2003
Section 6	34	November 2003	Section 9	2	November 2003
Section 6	35	November 2003	Section 9	3	November 2003
Section 6	36	November 2003	Section 9	4	November 2003
Section 6	37	November 2003	Section 9	5	November 2003
Section 6	38	November 2003	Section 10	1	November 2003
Section 6	39	November 2003	Section 10	2	November 2003
Section 6	40	November 2003	Section 10	3	November 2003
Section 6	41	November 2003	Section 10	4	November 2003
Section 6	42	November 2003	Section 10	5	November 2003
Section 6	43	November 2003	Section 11	1	November 2003
Section 6	44	November 2003	Section 12	1	November 2003
Section 6	45	November 2003	Section 12	2	November 2003
Section 6	46	November 2003	Section 13	1	November 2003
Section 6	47	November 2003	Section 14	1	November 2003
Section 6	48	November 2003	Section 15	1	November 2003
Section 6	49	November 2003	Section 15	2	November 2003
Section 6	50	November 2003	Section 15	3	November 2003
Section 6	51	November 2003	Appendix A	1	November 2003
Section 6	52	November 2003	Appendix A	2	November 2003
Section 6	53	November 2003	Appendix A	3	November 2003
Section 6	54	November 2003	Appendix A	4	November 2003
Section 6	55	November 2003	Appendix A	5	November 2003
Section 6	56	November 2003	Appendix A	6	November 2003
Section 6	57	November 2003	Appendix A	7	November 2003
Section 6	58	November 2003	Appendix A	8	November 2003
Section 6	59	November 2003	Appendix A	9	November 2003
Section 6	60	November 2003	Appendix A	10	November 2003
Section 6	61	November 2003	Appendix A	11	November 2003
Section 7	1	November 2003	Appendix A	12	November 2003
Section 7	2	November 2003	Appendix A	13	November 2003
Section 7	3	November 2003	Appendix A	14	November 2003
Section 7	4	November 2003	Appendix A	15	November 2003
Section 7	5	November 2003	Appendix A	16	November 2003

Section	Page	Date
Appendix A	17	November 2003
Appendix A	18	November 2003
Appendix A	19	November 2003
Appendix A	20	November 2003
Appendix A	21	November 2003
Appendix A	22	November 2003
Appendix A	23	November 2003
Appendix A	24	November 2003
Appendix A	25	November 2003
Appendix A	26	November 2003
Appendix A	27	November 2003
Appendix A	28	November 2003
Appendix A	29	November 2003
Appendix A	30	November 2003
Appendix A	31	November 2003
Appendix A	32	November 2003
Appendix A	33	November 2003
Appendix A	34	November 2003
Appendix A	35	November 2003
Appendix A	36	November 2003
Appendix A	37	November 2003
Appendix A	38	November 2003
Appendix A	39	November 2003
Appendix A	40	November 2003
Appendix A	41	November 2003
Appendix A	42	November 2003
Appendix A	43	November 2003
Appendix A	44	November 2003
Appendix A	45	November 2003
Appendix A	46	November 2003
Appendix A	47	November 2003
Appendix A	48	November 2003
Appendix A	49	November 2003
Appendix A	50	November 2003
Appendix A	51	November 2003
Appendix A	52	November 2003
Appendix A	53	November 2003
Appendix A	54	November 2003
Appendix A	55	November 2003
Appendix A	56	November 2003
Appendix A	57	November 2003
Appendix A	58	November 2003
Appendix A	59	November 2003
Appendix A	60	November 2003
Appendix A	61	November 2003
Appendix A	62	November 2003
Appendix A	63	November 2003
Appendix A	64	November 2003
Appendix A	65	November 2003
Appendix A	66	November 2003
Appendix A	67	November 2003
Appendix A	68	November 2003
Appendix A	69	November 2003
Appendix A	70	November 2003
Appendix A	71	November 2003
Appendix A	72	November 2003
Appendix B	1	November 2003
Appendix B	2	November 2003
Appendix B	3	November 2003
Appendix B	4	November 2003
Appendix B	5	November 2003
Appendix B	6	November 2003
Appendix B	7	November 2003
Appendix B	8	November 2003

Contents

Section 5 Prevention and mitigation of TRFs using non-HUMS technologies

Section 6 Advanced Flight Simulator trials

Section 7 Emergency procedures and advice

Section 8 Training

Foreword

The research reported in this Paper was jointly funded by the Safety Regulation Group of the UK Civil Aviation Authority, and the Defence Procurement Agency of the UK Ministry of Defence (MoD). The work was instigated at QinetiQ, Bedford in response to the conclusions and recommendations of the UK MoD Tail Rotor Action Committee report to the UK MoD Helicopter Airworthiness Maintenance Group, and in response to the findings of the Helicopter Human Factors Working Group reported in CAA Paper 87007 (Recommendation 4.1.18). The Helicopter Human Factors Working Group was formed in response to Recommendation 1 of the Report of the Helicopter Airworthiness Review Panel (HARP Report - CAP 491).

The CAA supports the conclusions and recommendations of the research, and offers the following comments on the five main areas of recommendations:

i) Airworthiness Design Requirements:

CAA supports the recommendations relating to the airworthiness design requirements and will endeavour to promote them by inclusion in the inventory of tasks for the new European Aviation Safety Agency (EASA). EASA assumed responsibilty for all certification requirements in September 2003.

ii) Prevention and Mitigation of TRFs using HUMS Technology:

Since this research was commissioned, in 1999 CAA mandated HUMS for all helicopters carrying more than 9 passengers in the UK. It is noted that the first generation systems currently in service have the capability to avoid 80% of the failures that even a developed HUMS has the potential to avoid. Although HUMS is currently only fitted to larger helicopters, CAA anticipates that as technology advances health monitoring systems for smaller and simpler helicopters will become increasingly viable. In addition, separate CAA-funded research (reported in CAA Paper 99006) has demonstrated the potential of advanced data processing tools such as neural networks to improve the effectiveness of HUMS; further work to promote the use of such techniques is under way. CAA concurs that the introduction of vibration health monitoring derived in-flight warnings is unlikely in the short or medium term due to the technical challenges of providing reliable and accurate diagnoses in-flight.

iii) Prevention and Mitigation of TRFs using non-HUMS Technology:

CAA has already drafted a Notice of Proposed Amendment (NPA) to the current JAA certification requirements with the aim of closing the regulatory gap (i.e. rotor control systems are currently neither required to be fail safe by design nor to undergo a Design Assessment as is the case for rotor drive systems), identified by the research in respect of tail rotor control systems. This initiative will be promoted to EASA for action.

iv) Emergency Procedures and Advice:

CAA proposes to distribute this paper to helicopter manufacturers and encourage them to review the flight crew emergency procedures and advice for their helicopters with a view to improving their content.

v) Training:

In respect of training issues, CAA proposes to draw the attention of training providers to the recommendations arising from the research in relation to the minimum simulator standards required, and the need to validate simulators and training programmes for tail rotor failures.

NB: It should be noted that, since completing the research reported in this paper, JAR-STD 1H has replaced FAA AC 120-63 as the civil rotorcraft criteria for simulation validation within JAA states. Although there are implications of this change in terms of some of the detail in Section 8 of this report, the overall message remains unaltered.

Safety Regulation Group

November 2003

Executive summary

This report is the deliverable from the QinetiQ research project 'Helicopter Tail Rotor Failures' carried out for the Civil Aviation Authority (CAA) under contract 7D/S/980, awarded to the Defence Evaluation and Research Agency (DERA) in 1997. The project was co-funded by the Ministry of Defence (MOD) Defence Procurement Agency. DERA and/or QinetiQ are referred to hereafter as QinetiQ.

The project comprised a study of tail rotor failures (TRFs) and their consequences. The motivation for the study was the overwhelming evidence gathered by the UK Tail Rotor Action Committee (TRAC) that TRFs were occurring at rates much greater than the airworthiness design standards require. This was true for both tail rotor drive and control systems, the former in particular, and applied to both civil and military types. The principal aims of the study were to analyse and quantify the nature and extent of the problem, and explore ways to reduce failure/accident rates and/or mitigate their effects in the future. In addition, existing training procedures and handling advice were examined and means of improvement suggested to prepare aircrew better for the effects of TRFs. Such failures are usually time critical events, requiring the pilot to take specific actions within a couple of seconds to avoid an uncontrollable, and hence catastrophic, situation developing. The study was not intended to address type-specific solutions, but rather to identify key airworthiness, technology and training aspects that may ultimately reduce the incidence and/or criticality of TRFs. It should be noted, however, that advice to aircrew on TRF management and recovery must be defined on a type-specific basis.

There are two major types of TRF:

a) A TR drive failure (TRDF) is a failure within the TR drive system with consequent (usually total) loss of TR thrust. Example causes are internal fatigue or external impact resulting in a broken drive shaft.

b) A TR control failure (TRCF) is a failure within the TR control system such that normal pilot control of TR thrust has been partially or totally lost. Example causes are internal wear or external impact resulting in a severed control cable. The resultant TR applied pitch, or power, could be free to fluctuate, or may be fixed anywhere between high pitch (HP) or low pitch (LP) setting, including that of the current trim pitch (TP).

Both of these TRFs are time critical emergencies. The pilot has to identify and diagnose the TRF type and react with the correct control strategy within a few seconds (or less), to prevent the aircraft departing into an uncontrollable flight state. Even if the pilot recovers from the initial transients, yaw (pedal) control will have been lost and the ability to manoeuvre safely and carry out a safe landing will have been significantly degraded. The TR and its drive and control systems are clearly flight critical components and should be designed so that their probability of failure is 'extremely remote'. The airworthiness design requirements for UK military and civil aircraft define 'extremely remote' as being less than 10-6 [1] and between 10-7 and 10-9 [2,3] per flight hour respectively.

Royal Air Force Handling Squadron expressed concerns over the advice provided to UK military aircrew in the event of TRFs over many years and, as a result, the MOD/CAA/industry TRAC was formed [4]. This group had the objective of reviewing UK military and civil accident and incident data (collectively described as occurrences) in detail, and recommended actions that would reduce TRFs and mitigate against their causes and consequences. The concept of technical and operational causes was developed:

- Technical causes are where component/system failures are the causes of occurrences. These comprise those internal to the drive train/controls and those external, which include aircraft parts (e.g. detached panels) striking the TR.
- Operational causes are where component/system failures are the result of occurrences. These include the TR striking the ground, obstructions or Foreign Object Damage (excluding aircraft parts), and the apparent loss of yaw control previously known as Gazelle 'Fenestron stall'.

The review of occurrence data indicated that the TRF rate due to technical causes is significantly worse than even the military requirement. Another concern was the relatively high TRF accident rate due to operational causes. The operating environment is such that the risk of collision with obstacles is relatively high and the TR is particularly vulnerable to damage. Deficiencies in the aircrew advice were also highlighted and programmes leading to the development of type-specific advice were recommended. At the time of writing, the only such study that has been completed is that for the Lynx [5]; however, QinetiQ and industry plans have been presented to the UK MOD for reviewing and revising military aircrew advice for the Merlin, Puma and Sea King types.

In addition to initiating the TRF advice activities, TRAC also recommended the need for a review of airworthiness requirements for helicopter TR systems. The evidence that TRs were, generally speaking, not meeting the spirit of airworthiness requirements, was stark and compelling. TRAC judged that work was required to establish how the airworthiness requirements could be changed to reinforce the criticality of the TR system, and what kind of technologies could mitigate against the adverse effects of TRFs.

The present project flowed from these recommendations, and the following primary objective was defined:

> 'To build on previous work to establish improved requirements, improve aircrew emergency advice and to make recommendations on emergency systems that might ultimately reduce the incidence and/or criticality of a tail rotor failure.'

The outline plan included a literature search, analysis of occurrence data, ground-based piloted simulation trials on the QinetiQ Bedford Advanced Flight Simulator (AFS) to investigate both handling qualities aspects of TRFs and potential mitigating technologies, and an assessment of extant training simulators. The defined tasks were:

a) To review and update the nature and extent of the TRF problem. This section of the research would: extend the review of occurrence data performed by TRAC to include available foreign civil and military data; update the UK civil and military data content; and characterise and summarise the complete occurrence experience. A search and review of all literature was also to be performed and reported.

b) To review relevant technologies which could potentially be utilised either to reduce the incidence of TRFs or mitigate their effects. In particular, the relevance of the conclusions of the ground-based simulator trials (conducted previously for the MOD) and any other work identified by the literature survey to civil aircraft operation was to be established and reported.

c) To assess potential solutions for reducing the occurrence and/or mitigating the effects of TRFs. These included a larger fin, emergency deployable fin, air brake devices, TRDF annunciator, Spring Bias Unit (SBU), Health and Usage Monitoring Systems (HUMS), TR strike warning, power chop function and Back-up Control Systems (BUCS). These measures were to be assessed with reference to the occurrence data, practicability, and benefits.

d) To review the existing airworthiness requirements material and make recommendations for additions and/or changes. The material relating to TR systems contained in the current military [1] and civil [2,3] certification requirements were to be reviewed in light of the findings of 1, 2 and 3, above. Recommendations for any additions and/or modifications were to be substantiated. This review was to include an examination of the handling qualities requirements associated with the three phases of a TRF (recovery, post-TRF flight and landing).

e) To review the existing emergency procedures and handling advice and make recommendations for change. This section of the project was to review the emergency procedures and handling advice relating to TRFs for all current UK military helicopter types and all civil aircraft types currently on the UK register, commenting on its usefulness. Means of establishing optimum handling advice and techniques for validating them were to be investigated and reported. It should be noted, however, that generation of new aircrew advice for individual types was not within the scope of this project.

f) To review military and civil practice regarding pilot training and make recommendations for simulator requirements to improve the effectiveness of training. The issues of fidelity and means of validation of the flight simulators utilised for pilot training were also to be reviewed and reported. Allowance was to be made for visiting and assessing two representative flight training simulators.

Task 1 was carried out principally by Stewart Hughes Limited (now trading as Smiths Aerospace Electronic Systems – Southampton (SAES-S), part of the Smiths Group, and referred to hereafter as SAES-S) [6]. Task 2 was performed by SAES-S and GKN Westland Helicopters Limited (now Westland Helicopters Limited (WHL), part of AgustaWestland, and referred to hereafter as WHL) [6,7]. Task 3 was carried out by WHL [7] and QinetiQ who conducted a simulation trial using the QinetiQ Bedford AFS. Task 4 was carried out within QinetiQ and included a second ground-based simulation trial. Task 5 was performed by WHL [8], who also supported QinetiQ in conducting Task 6. The simulation trials were conducted using a Lynx AH Mk 7 model, modified as appropriate to represent a variety of yaw stiffness and damping characteristics, and to simulate the effects of mitigating technologies. The main rotor stiffness was also modified to investigate the response of a lower effective hinge offset main rotor, typical of civilian helicopters. Almost 50 hours of motion-based, pilot-in-the-loop simulation were performed over the two simulation trials.

The summarised conclusions of the project are as follows:

The nature of TRFs: The management and control of a TRF can be assessed in three phases:

a) Transient: the failure transient and recovery to a safe flight condition.

b) Manoeuvre: manoeuvring in the failed condition.

c) Landing: the ability to perform a successful landing.

The ability of the aircrew to fly the aircraft within defined safety and performance standards within the three phases will depend on a number of key aspects. These include aircraft configuration, the flight condition prior to failure (including speed and altitude), the pilot’s attentiveness, the pilot’s training and skill, the TRF type and cues, and the responsiveness of the aircraft. Depending on the phase of flight and the TRF type, TRFs result in rapid pitch, roll and yaw excursions. Even if immediate and appropriate action is taken, pilot workload and disorientation can be very high. If such action is not taken, there is a serious risk of aircrew injury and airframe and collateral damage. With a standard pilot intervention time (PIT) of 2 seconds, it was shown that TRDF at high speed results in a transient sideslip which is likely to be beyond the structural limits of the aircraft. Height lost can be as much as 600 feet depending on the collective control strategy used. In the hover, there appears to be little that can be done to avoid the spin entry caused by a TRDF with the same PIT. Simulated recovery from HP TRCFs in both forward flight and in the hover was very difficult. A failure in the hover leads to a rapid build-up in yaw and the survival chances without significant damage are low, even in the low hover unless a landing is made positively and rapidly. LP TRCFs are similar in some respects to TRDFs, except that the TR continues to provide some yaw stiffness and damping in forward flight, and damping in the hover. TP TRCFs are very benign compared to the other TRF types.

The extent of TRFs: Analysis of a database of 344 TRF occurrences, constructed for this study from UK, US, Canadian and New Zealand sources, showed that accident rates across the various fleets averaged between 9.2 and 15.8 per million flying hours. The largest causes of TRF are either the TR striking or being struck by an object, which causes approximately one half of all TRF occurrences and fatalities, and failure of the TR drive system, which causes approximately one third of all TRF occurrences and fatalities. TR drive shafts, gearboxes and couplings are chiefly responsible for the latter. The largest number of TRF occurrences (27%) and fatalities (56%) for any single phase of flight occur during transit. TR torque is typically higher in the hover, take-off and landing phases (where 51% of occurrences take place) when compared with the other phases of flight (41% of occurrences). Thus, with respect to the relative duration spent in these phases, the high torque phases exhibit disproportionately large numbers of occurrences, including those caused by failure of the tail drive system, but particularly for tail/object impact. The UK MOD type most subject to failure is the Lynx (combined Service rate of 33.2 per million flying hours). Other types which stand out as exceeding the airworthiness design requirements by a dangerous margin are the MOD Puma (24.0) and Sea King (22.8) and the US Navy and Marine Corps AH-1 (19.5) and SH-2 (19.3).

Airworthiness design requirements: The attitude excursions during the transient phase of a TRF are critical to the pilot being able to achieve a successful recovery and featured as the primary response characteristics of interest during the piloted simulation trials. In the US handling qualities requirements standard ADS-33D [9], the allowable response transients following system failures are described in terms of handling qualities defined as Levels 1, 2 and 3 (in increasing order of handling qualities deficiencies). The attitude and acceleration response criteria, without failure warning and cueing devices, applicable to hover/low speed and near-Earth forward flight conditions are based on the aircraft displacement after 3 seconds without any pilot action. The aircraft would be displaced by about 30 feet (10 m) in all directions at the upper excursion limits. This military standard considers nap-of-the-Earth operations where tactical use is made of the ground for stealth, and such transient excursions are likely to result in a collision. It is suggested that such criteria are equally applicable to civil helicopter operations close to the ground. For up-and-away forward flight conditions, the requirements are based solely on staying within the Operation Flight Envelope (OFE).

Having recovered from the failure, the pilot's next action will depend upon the type of failure and the initial flight condition. The critical response that determines the capability to manoeuvre with power on will be the yaw response to collective which are described in ADS-33D in terms of yaw rate to height rate response. In terms of manoeuvrability, the ability to turn on cyclic without losing control is characterised by the turn co-ordination criteria, expressed in ADS-33D in terms of the ratio of sideslip to roll attitude following a control input designed to generate a step change in aircraft attitude.

A review of the Joint Aviation Requirements JAR-27 [2] and JAR-29 [3] by QinetiQ identified a regulatory gap relating to TR control system failures – current designs are neither pushed, by regulation, towards fail-safe solutions through redundancy (the preferred option where practical), nor to higher 'simplex' integrity through detailed design assessment. A two-path solution has been proposed as practicable and appropriate:

a) To require all practicable precautions to be taken to prevent single failures causing loss of continued safe flight and landing (i.e. require redundancy along the lines of that found in JAR25.671).

b) Where it is considered that redundant systems are impractical, to require justification of this and require that a design assessment be performed on the solution selected. This assessment shall include a detailed failure analysis to identify all failure modes that will prevent continued safe flight and landing, and identification of the means provided to minimise the likelihood of their occurrence.

Prevention and mitigation of TRFs using HUMS technology: Monitoring functions provided by current HUMS were assumed to be:

- TR drive shaft vibration
- TR drive shaft hanger bearing vibration
- Intermediate and TR gearbox vibration
- TR vibration
- Airframe vibration

Functions requiring HUMS development were:

- Gearbox and bearing temperature monitoring
- On-demand vibration checks
- Continuous rotor vibration monitoring
- TR rotational speed monitoring
- TR control input/output monitoring
- TR control mapping against flight parameters
- TR drive torque monitoring
- Gearbox oil level sensing
- Cockpit indication for vibration monitoring functions

Based on a detailed analysis of 31 example occurrence reports, coupled with estimated HUMS detection effectiveness, conservative estimates are that 49% of TRFs caused by failure of the TR drive system, and 18% of TRFs overall could have been prevented by current HUMS. This is achieved primarily through monitoring of the TR drive system using current HUMS technology as an aid to maintenance. In addition, it is estimated that a development of the existing HUMS technology would have prevented or mitigated a further 15% of TRFs caused by failure of the TR drive system and 5% of TRFs overall. Furthermore, a detailed review of flight deck indications by the HHMAG [10] concluded that any HUMS flight deck indications should be presented as 'supplementary data' only (i.e. not 'alerts') unless acceptable false alarm rates can be achieved. Any indication provided must be associated with unequivocal crew action. The use of current and developed HUMS technologies alone will not bring the occurrence rate to an acceptable level; 78% of TRFs are unlikely to be prevented by HUMS and are caused predominantly through the TR striking, or being struck by an object. Other means are required to help avoid hazards, make the TR system less susceptible to damage (e.g. existing Fenestron and NOTAR technologies), and maximise the chances of a pilot successfully dealing with a failure that occurs in flight. Another technology proposed is a scanning laser tip strike warning system that would draw the pilot's attention to the actual position of an obstacle. The effectiveness of this technology in helicopters is so far unproven, but might have prevented a further 8% of all TRF occurrences.

Prevention and mitigation of TRFs using non-HUMS technologies: TRCF problems can be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch (such as provided on operation of some types of SBU or Negative Force Gradient (NFG) spring). Activation of such a system in the event of a control rod disconnection between the pedals and the servo or between the servo and the TR (e.g. failure of control cables or hydraulic systems depending on the individual system type), can result in relatively benign TP TRCF conditions. A well designed warning device, which directed the pilot rapidly to the failure recovery, could be effective at reducing the PIT. An attitude command/attitude hold control system response type, particularly when associated with large (i.e. 20% or more) attitude hold authority, will significantly reduce the failure transients when compared to rate command systems. The use of controllable main rotor (MR) speed, together with appropriate collective control inputs, provides a very effective means of changing MR torque and reducing yaw rates during TRCFs in the hover.

The piloted simulation trials showed that additional fin area can be used to off-load the TR in forward flight, however considerable area is required to contain the initial yaw motion resulting from a TRDF. Additional fin area can also dramatically reduce the sideways flight capability. Assuming it is fixed (i.e. no rudder), such a fin could be a disadvantage in TRCF cases that have resulted in high TR thrust conditions since the high fin lift will exacerbate the situation. A drag parachute has the ability to be retrofitted, requires a relatively small area to produce significant yaw stiffness and does not affect low speed performance. The deployment of the drag parachute helps to constrain heading and the drag component results in a reduced speed for the given power level. It should be noted, however, that deployable devices such as this may not suppress the initial transients depending on the deployment time. A twin TR system could offer many benefits; however, it should be associated with a twin drive shaft system and duplex controls for the maximum benefit to be realised.

From a detailed analysis of 29 example occurrence reports, it is considered that the various prevention and mitigation technologies would have produced a beneficial effect in 90% of all the cases and in 88% of the cases caused by failure of the TR drive system. If the retrofit devices alone are considered (i.e. precluding twin TR/fan with duplex TR drive) these proportions would be 79% of all cases and 69% of cases caused by failure of the TR drive system. All cases caused by impact between the TR and an object would have benefited. In many cases more than one technology would have been beneficial. The technologies providing benefit in most cases were the drag parachute, inflatable fin and twin TR/fan with duplex TR drive. The in-line ducted fan and variable camber fin solutions also featured to a lesser extent and, for the TRCF cases, the SBU-type devices were largely beneficial. Most of the other technologies were not judged to be beneficial in the limited number of cases studied.

Emergency procedures and advice: The only complete method of determining the applicability of the advice given to aircrews would be to undertake a validation exercise on each aircraft type. The validation exercise cannot be generic because of the variation in possible failure modes, the basic fuselage stability characteristics and control systems characteristics. It must therefore be type-specific and is beyond the scope of this study. The validation process has to be undertaken against a set of defined criteria, which should be stated with the advice given. During the previous Lynx validation exercise [5] the following criteria were developed and are considered to be generally applicable[1]:

Type 1: Validation provided by a full in-flight demonstration of the recovery technique.

Type 2: Validation provided for the recovery technique being demonstrated using the best available engineering calculations coupled with piloted simulation.

Type 3: Validation provided for the recovery technique based on the best engineering calculations only.

Ideally, all validation of advice and recovery techniques should aim to achieve Type 1 validation. However, from a practical standpoint, TRDFs can only be demonstrated by piloted simulation and therefore the associated recovery techniques can, at best, only achieve Type 2 validation. On this basis, the Lynx TRF advice was validated to Type 1 for TRCFs and Type 2 for TRDFs. Of the 36 types whose advice was analysed, only the Lynx provides validated advice for both TRDFs and TRCFs. The standard of advice varies not only between manufacturers but also between marks of aircraft. The majority described the major symptoms associated with TRDFs, however, only 14% considered the loss of components at the tail pylon and identified the possible consequences of a major change in the aircraft centre of gravity. Only 17% discussed a defined TR pitch condition in the event of a control circuit failure. Advice on the appropriateness of using a power and speed combination during recovery from a TRDF was offered by only 53%. Control circuit failure was not considered at all by one third of the types. The variation in the standard of advice would suggest that there is considerable room for improving the level of advice currently given in the Aircrew or Flight Manuals (AM/FMs).

Training: Nine training simulator facilities responded to a questionnaire aimed at assessing the level of TRF simulation training provided to aircrews and instructors. More than half of the facilities were commissioned in the 1980s, and two thirds employ simulators equipped with six degree of freedom motion systems. Two thirds reported some degree of flight data validation over the OFE, but only the three Lynx simulators are likely to have benefited from any form of TRF validation. All of the respondents provide some form of TRF diagnosis and recovery instruction, although this was not a formal part of the teaching course in at least one case. Both TRDFs and TRCFs are covered in some form by most, but it is unclear how realistically they are modelled. In some cases it was stated that the rate of recovery from simulated TRFs is improved dramatically by the training provided, but it remains unclear how successful these recovery techniques would be in the actual aircraft. The highest confidence is thought to lie with the Lynx simulators due to the techniques having been validated through QinetiQ/WHL flight test and ground-based simulation studies.

1. In [5] the term Levels was used to denote the degree of advice validation. The term Level has been superseded by Type to avoid an association with Handling Quality Levels. Thus Level 1 is superseded by Type 1 etc.

There is evidence that some flying training schools discuss TRFs and demonstrate TRCFs in flight to a limited extent.

Criteria for validation of training simulators were formulated by the US Federal Aviation Administration in 1994 and are in the process of being formulated in a similar fashion by the Joint Aviation Authorities Committee [11]. There are four standards ranging from Level A to Level D (the highest). The first rotary wing facilities to be certified to Level C and Level D (currently only one Level D) were commissioned in 1998.

The investment that the UK MOD is providing over the next few years will result in half of all European military motion-based helicopter training simulators being situated in the UK [12]. Recommendations have been made to the UK MOD for further study into how the civil simulator requirements may be tailored to the military environment.

Recommendations: The recommendations of the project are numerous and are detailed within individual Sections of this report. The major recommendations are as follows:

- It is recommended that the JARs be amended to provide the two-path solution to closing the regulatory gap in respect of TR control systems:
  - i) To require all practicable precautions to be taken to prevent single failures causing loss of continued safe flight and landing (i.e. require redundancy along the lines of that found in JAR25.671).
  - ii) Where it is considered that redundant systems are impractical, to require justification of this and require that a design assessment be performed on the solution selected. This assessment shall include a detailed failure analysis to identify all failure modes that will prevent continued safe flight and landing, and identification of the means provided to minimise the likelihood of their occurrence.

It is recommended that the ADS-33D failure transient limits, collective to yaw requirements and sideslip excursion limitations are used as a means of quantification in the failure modes and effects analysis, as part of the two-path solution.

Manufacturers should be required to analyse the effect of TRFs and, where these effects are significant, provide at least Type 2 validated aircrew advice. Where such advice is not provided, it is recommended that advisory operational restrictions be provided (similar to the H-V diagram for engine failures). Such restrictions could also be realised through the inclusion of a reference to flight control/handling characteristics following TRFs in Sub-Part B of JAR-27 and JAR-29.

- The fitting of appropriately designed HUMS, focussed on (but not limited to) monitoring TR drive system failure is strongly recommended.
- Action should be taken to further define the HUMS required for specific types or categories of helicopter. This should take into account the specific failure types, the handling qualities of the aircraft post-failure and economic factors.
- TRCF problems should be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch (e.g. as currently used in some types of SBU). The fail-safe pitch should function in the event of a control rod disconnection between the pedals and the servo or between the servo and the TR. Further type-specific studies should be carried out to determine the mechanisms and settings required, and to investigate the transient behaviour on TRCF and activation of the device.

- MR speed control (increase and decrease from trim) should be provided to the aircrew to assist in recovery from TRCFs in the hover.
- Deployable devices, such as an inflatable fin and drag parachute, should be investigated for retrofit on existing types and incorporated in the design of future types to provide additional yaw stiffness in the event of TRF.
- It is strongly recommended that type-specific piloted simulation and, where possible, flight test programmes are put in place to develop advice validated to a minimum of Type 2 (demonstration using the best available engineering calculations coupled with piloted simulation) for TRFs in general, and Type 1 (full in-flight demonstration of the recovery technique) for TRCFs.
- The minimum training simulator certification level appropriate for TRF training should be Level C as defined in US Federal Aviation Administration Advisory Circular AC 120-63. Inherent in this is the recommendation that all training simulators are built with motion available in all six degrees of freedom (surge, sway, heave, roll, pitch and yaw), and that the field of view be as representative as possible, particularly with respect to the provision of ground speed visual cues.
- Where TRF flight test data or validated TRF advice cannot be provided, subjective assessment of training simulators should be carried out against the experience of those who have suffered failures. Where not undertaken already, such experience should be shared within the piloting community, perhaps collated by the civil authorities or pilots associations and made readily available to the training organisations.
- Although full realism cannot be provided in most cases, it is recommended that all flying schools at least demonstrate the effects of extreme TR pitch jams to aid diagnosis, and that techniques are explored by the students where it is safe to do so.

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Section 1 Introduction

1 Background

This report is the deliverable from the QinetiQ research project 'Helicopter Tail Rotor Failures' carried out for the Civil Aviation Authority (CAA) under contract 7D/S/980. The project, awarded to the Defence Evaluation and Research Agency (DERA) in 1997, was co-funded by the Ministry of Defence (MOD) Defence Procurement Agency. DERA and/or QinetiQ are referred to hereafter as QinetiQ.

1.1 **Tail rotor failures**: There are two major types of tail rotor failure (TRF):

a) A tail rotor drive failure (TRDF) is a failure within the tail rotor (TR) drive system with consequent (usually total) loss of TR thrust. Example causes are internal fatigue or external impact resulting in a broken drive shaft.

b) A TR control failure (TRCF) is a failure within the TR control system such that normal pilot control of TR thrust has been partially or totally lost. Example causes are internal wear or external impact resulting in a severed control cable. The resultant TR applied pitch, or power, could be free to fluctuate, or may be fixed anywhere between high pitch (HP) or low pitch (LP) setting, including that of the current trim pitch (TP).

Both of these TRFs are time critical emergencies. The pilot has to identify and diagnose the TRF type and react with the correct control strategy within a few seconds (or less), to prevent the aircraft departing into an uncontrollable flight state. Even if the pilot recovers from the initial transients, yaw (pedal) control will have been lost and the ability to manoeuvre safely and carry out a safe landing will have been significantly degraded. The TR and its drive and control systems are clearly flight critical components and should be designed so that their probability of failure is 'extremely remote'. The airworthiness design requirements for UK military and civil aircraft define 'extremely remote' as being a probability of less than 10^{-6} [1] and between 10^{-7} to 10^{-9} [2,3] per flight hour respectively.

1.2 **Tail Rotor Action Committee**: Royal Air Force Handling Squadron (RAFHS) had expressed concerns over the advice provided to UK military aircrew in the event of TRFs over many years and, as a result, a MOD/CAA/Industry Tail Rotor Action Committee (TRAC) was formed [4]. This group had the objective of reviewing UK military and civil accident and incident data (collectively described as occurrences) in detail, and recommended actions that would reduce TRFs and mitigate against their causes and consequences. The concept of technical and operational causes was developed:

- Technical causes are where component/system failures are the *causes* of occurrences. These comprise those internal to the drive train/controls and those external, which include aircraft parts (e.g. detached panels), striking the TR.
- Operational causes are where component/system failures are the *result* of occurrences. These include the TR striking the ground, obstructions or Foreign Object Damage (excluding aircraft parts), and the apparent loss of yaw control previously known as Gazelle 'Fenestron stall'.

The review of occurrence data indicated that the TRF rate due to technical causes is significantly worse than even the military requirement. Another concern was the relatively high TRF accident rate due to operational causes. The operating environment is such that the risk of collision with obstacles is relatively high and the

TR is particularly vulnerable to damage. Deficiencies in the aircrew advice were highlighted and programmes leading to the development of type-specific advice were recommended. At the time of writing, the only completed study is that for Lynx [5]; however, QinetiQ and other industry plans have been presented to the UK MOD for reviewing and revising military aircrew advice for the Merlin, Puma and Sea King types.

In addition to initiating the TRF advice activities, TRAC also recommended the need for a review of airworthiness requirements for helicopter TR systems. The evidence that TRs were, generally speaking, not meeting the spirit of airworthiness requirements, was stark and compelling. TRAC judged that work was required to establish how the airworthiness requirements could be changed to reinforce the criticality of the TR system, and what kind of technologies could be employed to mitigate against the effects of TRFs.

1.3 **Generic study**: The present project flowed from the above recommendations, and the following primary objective was defined in the project Outline Management Plan (OMP) [6]:

> 'To build on previous work to establish improved requirements, improve aircrew emergency advice and to make recommendations on emergency systems, that might ultimately reduce the incidence and/or criticality of a tail rotor failure.'

2 Project scope

The outline plan included a literature search, analysis of occurrence data, ground-based piloted simulation trials on the QinetiQ Bedford Advanced Flight Simulator (AFS) to investigate both handling qualities aspects of TRFs and potential mitigating technologies, and an assessment of extant training simulators. The defined objectives were:

1) To review and update the nature and extent of the TRF problem. This section of the research would: extend the review of occurrence data performed by TRAC to include available foreign civil and military data; update the UK civil and military data content; and characterise and summarise the complete occurrence experience. A search and review of all relevant literature was also to be performed and reported.
2) To review relevant technologies which could potentially be utilised either to reduce the incidence of TRFs or mitigate their effects. In particular, the relevance of the conclusions of the ground-based simulator trials (conducted for the MOD prior to this project) and any other work identified by the literature survey to civil aircraft operation was to be established and reported.
3) To assess potential solutions for reducing the occurrence and/or mitigating the effects of TRFs. These included a larger fin, emergency deployable fin, air brake devices, TRDF annunciator, Spring Bias Unit (SBU), Health and Usage Monitoring Systems (HUMS), TR strike warning, power chop function and Back-Up Control Systems (BUCS). These measures were to be assessed with reference to the occurrence data, practicability, and benefits.
4) To review the existing airworthiness requirements material and make recommendations for additions and/or changes. The material relating to TR systems contained in the current military [1] and civil [2,3] certification requirements were to be reviewed in light of the findings of 1, 2 and 3, above. Recommendations for any additions and/or modifications were to be substantiated. This review was to include an examination of the handling qualities

requirements associated with the three phases of a TRF (recovery, post-TRF flight and landing).

5) To review the existing emergency procedures and handling advice and make recommendations for change. This section of the project was to review the emergency procedures and handling advice relating to TRFs for all current UK military helicopter types and all civil aircraft types currently on the UK register, commenting on its usefulness. Means of establishing optimum handling advice and techniques for validating them were to be investigated and reported. It should be noted, however, that generation of new aircrew advice for individual types was not within the scope of this project.
6) To review military and civil practice regarding pilot training and make recommendations for simulation requirements to improve the effectiveness of training. The issues of fidelity and means of validation of the flight simulators utilised for pilot training were also to be reviewed and reported. Allowance was to be made for visiting and assessing two representative flight training simulators.

Objective 1 was addressed first. Objectives 2 and 3 were separated into HUMS and non-HUMS prevention and mitigation technology studies, from which a selection was assessed in the second of two ground-based simulation trials. The first such trial was carried out to quantify the specific TRF handling qualities criteria, a need identified from the certification requirements study for objective 4. Objectives 5 and 6 were carried out toward the end of the project.

3 Report structure

The Report contains 10 main Sections. Section 2 describes the nature and extent of the TRF problem, including a summary review of the occurrence database. Section 3 addresses TR airworthiness requirements, reviewing the content of existing military and civil requirements and proposing relevant changes. Sections 4 and 5 describe the respective HUMS and non-HUMS prevention and mitigation technologies investigated during the study, while the AFS trials supporting the airworthiness requirements and mitigating technology studies are reported in Section 6. Sections 7 and 8 address emergency procedures and training respectively, and include reviews of current practice and recommendations for change. Sections 9 and 10 consolidate the programme’s conclusions and recommendations. Two appendices support the main body of text; details of the potential impact of prevention and mitigation technology concepts on a number of occurrences are discussed in Appendix A; Appendix B comprises a discussion paper giving a test pilot’s view of TRFs having participated in the AFS trials.

The most important conclusions reached and recommendations made are underlined throughout the report.

GKN Westland Helicopters Limited (now Westland Helicopters Limited (WHL), part of AgustaWestland), are referred to throughout this report as WHL. Bond Helicopters and Scotia Helicopter Services (now CHC Scotia Ltd, part of CHC Helicopter Corporation) are referred to throughout this report as CHC Scotia Ltd. Stewart Hughes Limited now trade as Smiths Aerospace Electronic Systems – Southampton (SAES-S), part of the Smiths Group, and are referred throughout this report as SAES-S.

Section 2 The Nature and Extent of Tail Rotor Failures

1 Introduction

The work reported on in this section covers objective 1 as defined in Section 1. The nature of TRFs is described in 2, the literature review is summarised in 3 and the results of the work to determine the extent of TRFs are provided in 4. Conclusions and recommendations from this section are given in 5 and 6 respectively.

2 The nature of tail rotor failures

2.1 Management and control of tail rotor failures

The TR provides three basic functions:

a) **Torque reaction**: this counters the effect of the yawing moment associated with the main rotor (MR).

b) **Directional stability**: the loaded TR inherently provides yaw stiffness and damping, providing directional stabilising moments following sideslip excursions.

c) **Yaw control**: by varying the collective pitch of the TR to alter the amount of torque reaction, the heading of the aircraft can be adjusted to generate a yaw rate or sideslip as required.

TRF management and control can be divided into three phases:

a) **Transient**: the failure transient and recovery to a safe flight condition.

b) **Manoeuvre**: manoeuvring in the failed condition.

c) **Landing**: the ability to perform a successful landing.

These phases of TRF management and control can be mapped against the basic TR functions as shown in Table 2-1, where an attempt is made to prioritise the effects of the various functions during the different phases. For example, during the transient phase, the loss of the TR's ability to provide torque reaction will dominate the situation; at this stage it is not important to be able to demand an aircraft heading.

Table 2-1 Functional priorities for the TRF phases

TRF phase	TR function		
	Torque reaction	**Directional stability**	**Yaw control**
Transient	High	Medium	Low
Manoeuvre	Low	High	Medium
Landing	Low	Medium	High

The various TRF types (described in 1 in Section 1) will require different levels of compensation for each of the lost or degraded TR functions. The effects on the TR function associated with the major types of TRF are given in Table 2-2. During a total TRDF there will be no contribution to torque reaction or directional stability and it will not be possible to directly control the helicopter's heading.

Table 2-2 Functional effects of the TRF types

TRF type	TR function		
	Torque reaction	**Directional stability**	**Yaw control**
TRDF	Lost	Lost	Lost
LP TRCF	Minimal	Degraded	Lost
HP TRCF	Excessive	Degraded	Lost

Primarily, it is the inherent response characteristics of the aircraft that determine the ability to compensate for the loss of TR functionality. In some cases (e.g. Lynx) the need for torque reaction has to be removed by shutting down the engines and entering autorotation. However, some helicopters (e.g. Dauphin) have sufficient inherent yaw stiffness to enable powered run-on landings to be performed. In a high hover the pilot may have time to enter autorotation and then shut down the engines, whereas in a low hover it would be preferable to shut down the engines and then cushion the landing with rotor thrust. The ability of the aircrew to fly the aircraft within defined safety and performance standards will depend on a number of key factors. These include: the aircraft configuration; the flight condition prior to failure (including speed and altitude); the pilot's attentiveness, training and skill; the failure type and cues; and the response characteristics of the aircraft, including the level of autostabilisation in the other axes.

2.2 Recovery from the failure transient

For TRDFs, and TRCFs where the post-failure pitch angle of the TR blades is different from the pre-failure trim position, the immediate effect is a yaw response. That is, (for anticlockwise main rotors), nose to starboard following a TRDF or LP TRCF, and nose to port following a HP TRCF. The level of initial yaw acceleration will depend on the nature of the failure, and the level of yaw rate and attitude build-up will depend on the forward speed. In hover, an unchecked TRDF will result in the yawing moment from the main rotor torque reaction spinning the fuselage at rates in excess of 100° sec^{-1}, perhaps even as high as 150-200° sec^{-1}. Typically, the higher the forward speed, the lower the yaw rate and attitude excursion as any natural directional stability of the aircraft will tend to reduce the severity of the motion. However, this is only true up to some value of sideslip, beyond which it is possible that directional stability can reverse, resulting in increased yaw rate and attitude excursions. Evidence from the Lynx TRF AFS trial [5] suggests that the ability of the pilot to successfully manage a forward flight failure is strongly related to the extent of the initial yaw/sideslip transient. If this exceeds 90°, then the pilot is unlikely to be able to recover, as the flight control problem is exacerbated by disorientation; if the yaw rate reduces to zero below about 30° yaw angle, then the pilot has a much greater chance of recovering from the failure. Accompanying the yaw excursions will be pitch and roll motion, which can further increase the risk of disorientation. An additional effect of any roll attitude transient is an increase in the main rotor disc angle of incidence, leading to an increased risk of the rotor over-speeding as the pilot reduces main rotor collective to contain the effects of the failure. The extent of the attitude excursions depends on the aerodynamic design characteristics of the fuselage and vertical stabiliser, the resulting directional stability, the type of attitude stabilisation present in the flight control system and the pilot’s control actions. It is clear that the extent of the transient attitude excursions is critical and should feature as one of the main handling parameters for investigation in the programme.

As a precursor to the presentation of results later in this report, Figure 2-1 and Figure 2-2 show sample results gathered from 'off-line' simulations of a TRDF using a Lynx model configuration (see Section 6). The Aeronautical Design Standard ADS-33D handling qualities Level 3/4 attitude boundary (explained in more detail in [7] and Section 3) is superimposed on the pitch and roll angle graph, and the sideslip Operating Flight Envelope (OFE) limit is superimposed on the sideslip graph. A baseline weight of 11200 lb was selected during the AFS trial work-up prior to the trials reported on in Section 6; this is heavy for a Lynx but was used to reduce the severity of a HP TRCF in the hover.

Figure 2-1 shows a set of aircraft responses following an instantaneous TRDF at a cruise condition of 140 kn (the TR thrust reduces to zero instantly at the failure). The immediate pilot action was modelled as a reduction to zero of MR collective after a 1 second pilot intervention time (PIT). The yaw rate peaks at about 60° sec^{-1} at about 2 seconds, the sideslip peaks at more than 60° at 2 seconds. Within 10 seconds the sideslip has reversed and is settling out at about 30°, the speed having reduced to about 120 kn at this stage. The rate of descent in this high-speed autorotation is more than 2000ft/min and the rotor speed is increasing above 120% at the 10-second point.

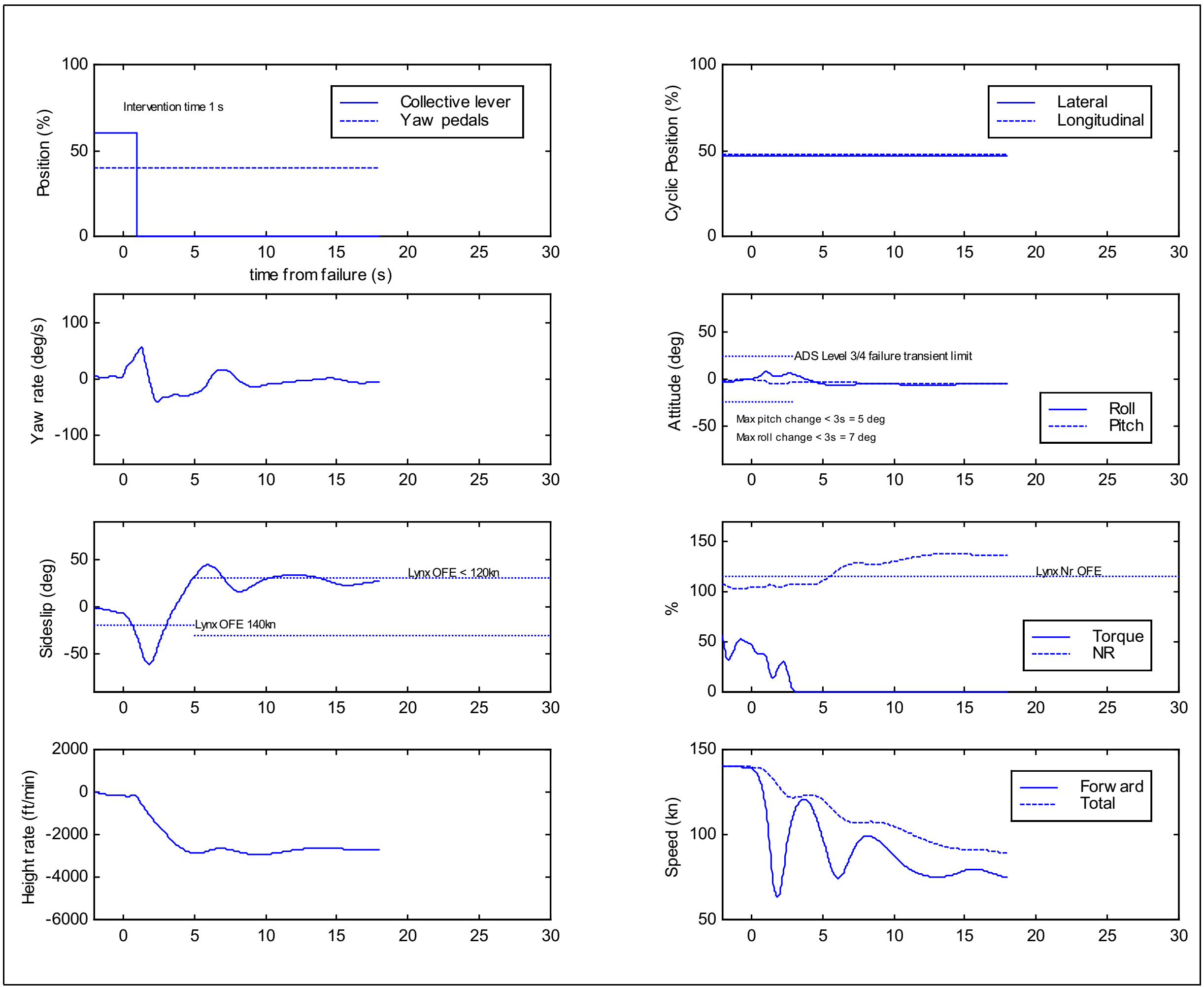

Figure 2-1 Off-line simulation of 140 kn TRDF with 1 s PIT

Figure 2-2 shows the effect of increasing the PIT to 2 seconds in the off-line simulation. In this case, as a result of the port sideslip transient, the aircraft rolls sharply to starboard by more than 60°. The increased disc incidence leads to a strong windmilling effect on the rotor causing it to speed up to about 150% of nominal value after about 4 seconds. The speed reduces below 100 kn in this time. This pattern of behaviour will be seen again later when the results of the piloted simulations are presented, including the varying degrees of mitigation from real pilot action. Other kinds of TRF result in different aircraft behaviour and require different pilot reactions; all require considerable pilot judgement and skill to recover.

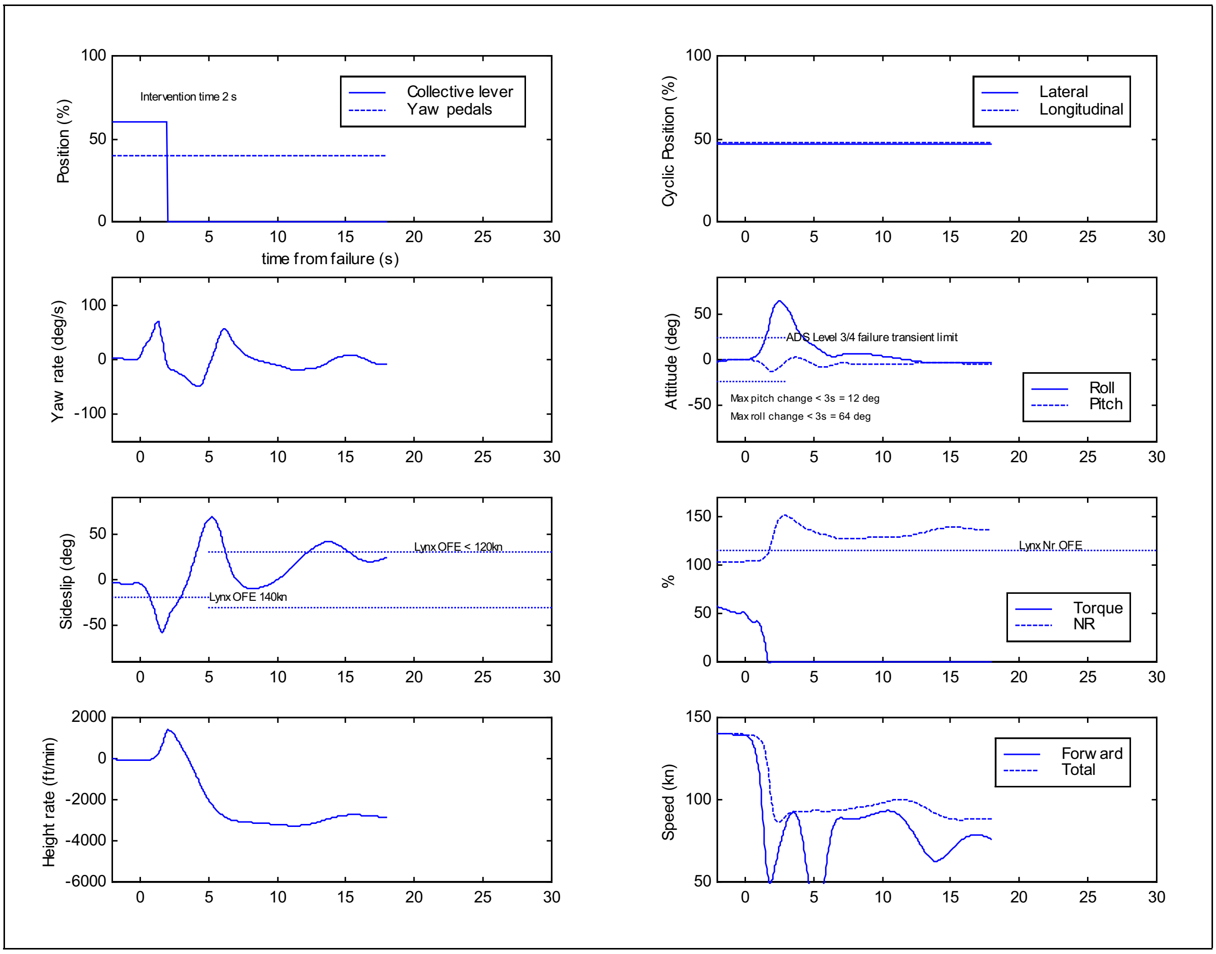

Figure 2-2 Off-line simulation of 140 kn TRDF with 2 s PIT

2.3 Manoeuvrability in the failed condition

Having recovered from the failure, the pilot's next action will depend on the type of failure and the initial flight condition. From a forward flight initial condition at cruise altitude, for example, the pilot will generally want to be able to accomplish two things:

a) Manoeuvre the aircraft to change heading, speed and altitude, including flying the aircraft into a flight condition for an approach to a landing. The handling qualities requirements for this manoeuvre phase relate to how well the pilot can turn the aircraft and establish a straight flight path, and will be described in Section 3 of this report.

b) If possible, find a power/speed combination for continued flight giving time to select a safe landing area. The ability to carry this out will depend upon the vehicle's inherent stability and the type of TRF, although there are some types where there is no acceptable power/speed combination, and an immediate autorotative landing is the only possibility.

2.4 Landing

Assuming that the pilot has established an approach flight profile the remaining tasks are to:

a) conduct a final deceleration to the required landing speed;

b) flare the aircraft while arresting the rate of descent with collective;

c) yaw the aircraft to line up with the flight path;

d) level the attitude just prior to touch down.

Most of these actions are critical to a successful landing, but aligning the aircraft with the flight path is arguably the most critical in terms of minimising the risk of rollover. The pilot no longer has direct yaw control and the workload in this phase is very high due to the need to co-ordinate these four different actions within a few seconds, particularly the co-ordination of height rate and yaw response. The occurrence data contain many cases where the pilot has successfully touched down following a TRF, but the aircraft has consequently turned over and suffered major damage. This programme did not include an investigation of ground contact dynamics or survivability technologies, since the simulation was not able to model such aspects adequately.

3 Literature review

The titles resulting from the literature search which are not directly referenced (see Section 12) are contained in Section 13. As can be seen from these Sections, only a few items of TRF research have been published in the public domain, and few provided significant input to the programme.

4 The extent of tail rotor failures

4.1 Introduction

This review of TRFs summarises the work carried out by Smiths Aerospace Electronic Systems - Southampton (SAES-S, part of the Smiths Group) for this programme [10]. The company was tasked to update the work carried out for the TRAC and to expand the database of statistics to include as much foreign data as possible. The aim of this part of the programme was to provide a comprehensive analysis of TRFs in order to characterise the problem as fully as possible.

In this summary, the salient conclusions from the SAES-S report are reproduced and the presentation of the data has been modified from the original reference. It should also be noted that some errors have since been discovered and the corrected data are presented herein. The reference contains more detailed descriptions of the database structure and classifications. This section starts by reviewing the analysis and conclusions from the TRAC study and then moves on to analyse the expanded dataset. The analysis includes a comparison of accident rates across the different fleets, an assessment of the distribution of the causes of TRFs and the variations across the national groupings. Also examined is the incidence of TRFs during different phases of flight and a comparison of the variations for different military types.

4.2 Review of TRAC statistics

The TRAC summary of helicopter TRF statistics covered the period 1971 to 1994 and included data from the three UK MOD accident databases. The civil data were taken from the CAA's Mandatory Occurrence Reporting System (MORS) for the period 1976 to 1993. The technical causes of TRF were categorised crudely into internal and external as defined in 1.1. TRDFs were found to be more prevalent than TRCFs by a ratio of approximately 3:1.

4.2.1 **UK Military statistics**: It was calculated that the ratio of internal to external causes was approximately 3:2. The TRAC report identified that the rate of TRF within the MOD fleets was significantly higher than the airworthiness target of no more that one per million flying hours. It was generally concluded that as the airframes of a particular fleet age there is an increased likelihood of TRF.

Out of a quoted total of 54, 31 occurrences were classified as accidents (MOD Categories 3,4 and 5), from a total of 2.25 million flying hours. The number of occurrences used to calculate the average rate due to technical causes of 13.8 per million flying hours must also have been 31. When these data were reviewed it was concluded that the 31 accidents included both technical and operational causes and that the total number of cases was in fact 53, from 3.63 million hours. In addition, the total number of technical occurrences was actually 33, resulting in a revised average occurrence rate due to technical causes of 9.1 per million flying hours. A résumé of the originally quoted and revised technical, operational, internal and external cause statistics is provided in Table 2-3. All operational causes have been regarded as external.

Table 2-3 Original and revised military TRAC statistics

Analysis	All occurrences								Accidents only			
	Technical		Operational		Internal		External		Technical		Operational	
Original	-	13.8	-	-	-	-	-	-	-	-	-	-
Revised	33	9.1	20	5.5	31	8.5	22	6.1	19	5.2	12	3.3
Key:	Quoted number						Rate per million flying hours					

Despite the overall errors, the individual type technical occurrence statistics presented in the TRAC report are unchanged however, and are reproduced in Figure 2-3. For clarity, data for the now out-of-service RN Wessex (rate 83.3) have not been displayed, and the dashed line indicates the UK military requirement limit. Non-operation of a type for a given Service is indicated by the absence of a rate.

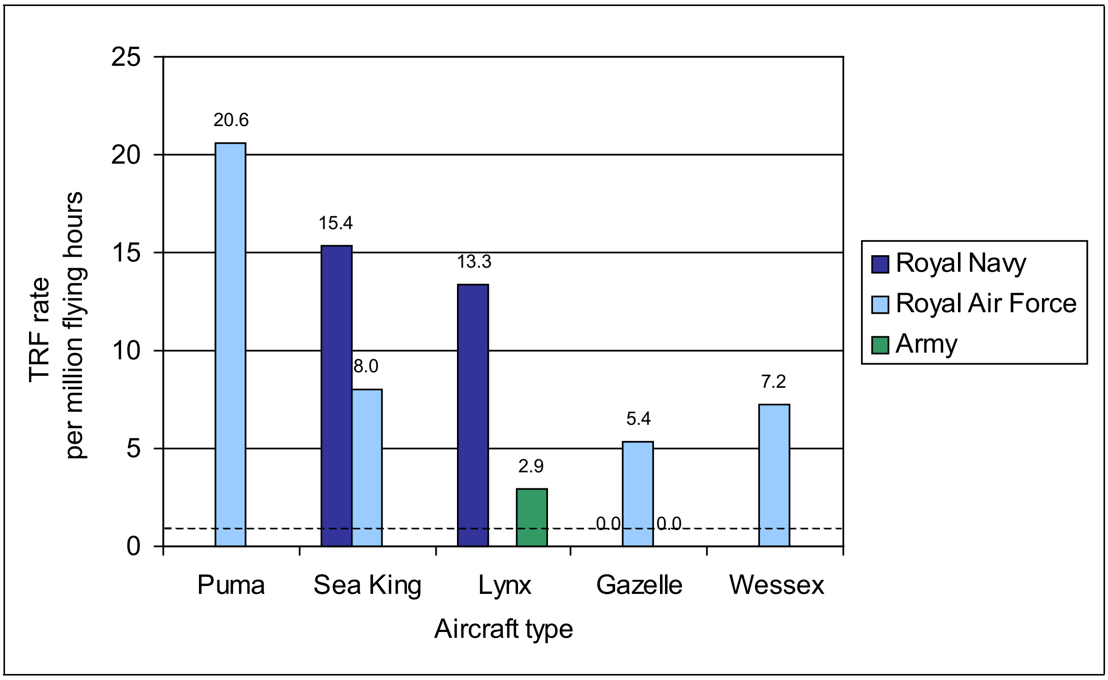

Figure 2-3 TRAC UK MOD technical TRF occurrences by type

4.2.2 **UK civil statistics**: A total of 45 occurrences, 20 of which were classed as accidents were identified within a span of 3.61 million hours. The ratios of internal to external causes of TRF overall was 2:1, and 3:1 for internal TRDF to internal TRCF. Analysis of these data by SAES-S revealed that incorrect criteria had been used for classifying accidents and, when the MORS criteria were used (see 2.4.4), 29 accidents were identified. The original and revised data for light and heavy helicopters (as defined in [2] and [3] and given in Table 2-4) are presented in Table 2-5.

Table 2-4 Weight categories

Category	Weight
Light	2730 kg or less
Heavy	more than 2730 kg

Table 2-5 Original and revised civil TRAC statistics

Analysis	All (3.611 M hours)				Light (1.219 M hours)				Heavy (2.392 M hours)			
	Occurrences		Accidents		Occurrences		Accidents		Occurrences		Accidents	
Original	45	12.5	20	5.5	34	27.9	16	13.1	11	4.6	4	1.7
Revised	45	12.5	29	8.0	33	27.1	23	18.9	12	5.0	6	2.5
Key:	Number						Rate per million flying hours					

4.2.3 **Summary of TRAC statistics**: The revised TRAC statistics reveal that the TRF accident rates for military and civil helicopters were 8.5 and 8.0 per million flying hours respectively; i.e. at least 8 times worse than even the military requirement.

4.3 Sources of data for current review of occurrences

For a more robust statistical analysis of TRFs it was necessary to expand the database to cover a greater number of flight hours. The programme plan sought to obtain data from as wide a field of operation as possible with the aim of capturing data from global sources, including Eastern Bloc nations. Unfortunately, data from the latter countries were not available, but information was gathered from the USA, UK, Canada and New Zealand which alone account for over 80% of the remaining known aircraft. Aircraft manufacturers were approached for material to be included in the analysis but, with the exception of WHL, the figures would not be released into the public domain.

The database compiled for this programme comprises data from 344 TRF occurrences relating to different time periods depending on the source. The period over which data were taken reflects their availability, particularly those readily available from computerised databases that have become accessible in recent years. The sources are summarised in Table 2-6.

Table 2-6 Occurrence data sources

Source	Period	Comment
UK Civil Aviation Authority	1976-1997	MORS data TRAC data (1976-1993)
UK MoD	1972-1997	DERA Farnborough (1972-1997) Royal Navy (1988-1997) Army Air Corps (1987-1997) Royal Air Force (1980-1997) TRAC data (1971-1994)
GKN Westland Helicopters Limited	1963-1997	All WHL supplied/manufactured helicopters including UK and foreign
Air Accidents Investigation Branch (UK)	1995-1997	Data from AAIB website and AAIB reports
National Transportation Safety Board (USA)	1990-1997	
Transportation Safety Board (Canada)	1993-1997	
New Zealand Civil Aviation Authority	1996-1997	

Summary data were obtained from the US Coast Guard, Navy and Marine Corps (USCG, USN, USMC) for their helicopter fleets, but the information was not detailed enough to be included in the occurrence database. These data have been used for fleet comparisons of accident rates only. The military contributions to the database were thus the 75 UK MOD cases plus 7 foreign military cases originating from the UK CAA records.

4.4 **Accident Classification**

As has been highlighted above, the definition of what constitutes an accident varies between sources. The CAA MORS database classifies accidents on the basis of the International Civil Aviation Organisation definition, which has been used for the current study:

> 'Occurrences associated with the operation of the aircraft which take place between the time when any person boards the aircraft with the intention of flight and such time as all persons have disembarked therefrom, in which: any person suffers death or serious injury by contact with any part of the aircraft; or the aircraft incurs damage which adversely affects its structural strength, performance or flight characteristics and would normally require major repair or replacement of the affected component; or the aircraft is completely missing.'

The MOD classification based on the category of damage has been retained with Categories 1 and 2 (minor damage, non-serious injury) being defined as incidents and Categories 3, 4 and 5 (major damage, serious injury and fatalities) as accidents.

The material gained from the foreign databases is classed by slightly different criteria. No reclassification of these records has been attempted for this study. This must be taken into consideration when reviewing the statistics as, for example, the US National Transportation Safety Board (NTSB) labels all entries on its system as accidents.

4.5 **Data fields recorded**

In an attempt to further the TRAC study and to gain a better understanding of the nature of TRFs, the number of data fields was increased to provide greater detail. The fields in the database were selected in order to acquire an overall picture of the event from the details of the aircraft to the phase of the flight in which the failure happened and the precise nature of the failure itself. Table 2-7 details the data fields employed.

Table 2-7 Occurrence database elements

Aircraft	Occurrence	Circumstances	Consequences
Manufacturer	Date	Operator	Accident/incident
Type	Failure type	Mission	Regained control
Model	Internal/external	Flight phase	Damage
Mark	Technical/operational	Investigating authority	Fatalities
Registration			Injuries
Weight band			

In addition to these data fields, the failure types were categorised in order to quantify the significant causes of TRFs in helicopters. The categories used for known causes are internal and external, sub-divided into components of the TR system, as shown in Table 2-8.

Table 2-8 Internal and external TRF causes

External	Internal
TR hitting an obstacle Object hitting the TR Loss of TR effectiveness	Failures of the structure supporting the TR drive. Failure of the TR drive: • TR drive shaft • intermediate or TR gearbox • drive shaft coupling • drive shaft hanger bearing • TR blade • TR hub component • vee belt TR pitch control system

4.6 **Overall fleet accident rates**

The TR-related accidents were compared for four large fleets of aircraft, and are shown in Figure 2-4. The overall rates are relatively consistent across the fleets, in the range 9.2 to 15.8 per million flight hours, but the differences in accident definition should be considered when making comparisons. The dashed line represents the UK military requirement limit. The data given in [10] indicate that 83% of the US NTSB occurrences were in the light category, unfortunately the hours for each category were not available so their rates are unknown. Note that all the other available US data were in the heavy category.

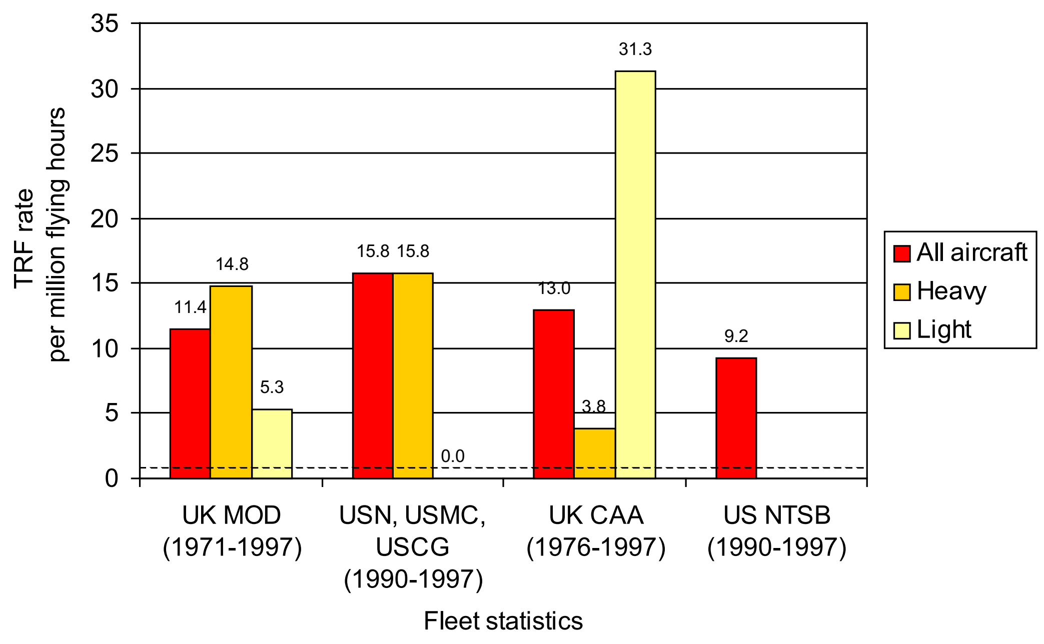

Figure 2-4 TRF accident rates for UK and US fleets

The overall UK civil and military rates are of similar order, as they were at the time of the TRAC analysis. The larger figures from this more recent study are due to the fact that more accidents have been identified, rather than any major increase in the accident rate in recent years.

It should be noted that the ratio of accident rates between the two weight categories is very different between the UK military and civilian fleets. This is thought to be due to the differences in the types of operation undertaken by the two fleets because of the operational conditions and roles performed by the different classes.

The more detailed examination in [10] has identified that there are considerable variations in the occurrence rate by aircraft type and that there is no annual trend to suggest that occurrence rates will converge on a consistent figure. With only a few occurrences each year the statistical basis for further conclusions becomes tenuous.

4.7 TRF occurrences by cause

The causes of TRFs for all aircraft included in the database (i.e. not including the US military) are shown in Figure 2-5. The TRAC UK civil data showed that the ratio of internally caused TRDFs (most likely due, but not limited to the TR drive system) to TRCFs (most likely due, but not limited to the TR control system) was 3.0:1. The ratio from the present database, of TRFs caused by the TR drive and control systems, is 3.6:1. It should also be noted that the external/operational causes account for 53% of the total.

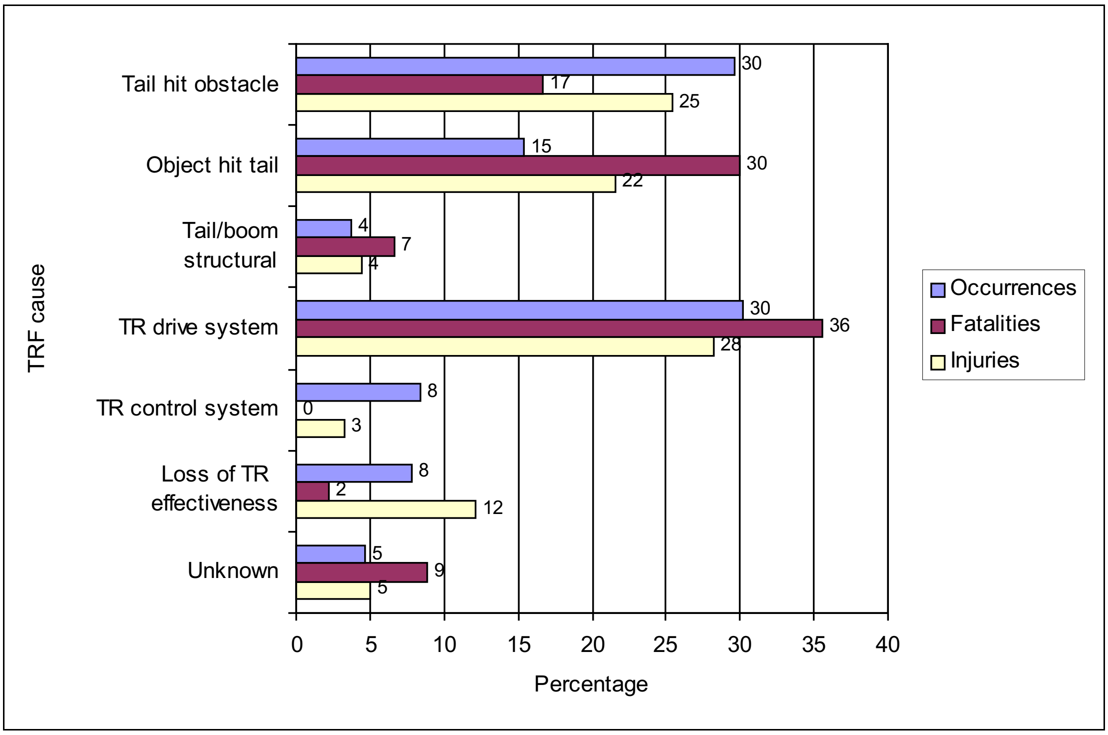

Figure 2-5 Distribution of TRF causes (all aircraft)

The TR drive system is shown to be the largest cause of TRFs (30%), resulting in the largest numbers of fatalities and injuries, but is closely followed by the TR striking or being struck by an object (combined total of 45%). The occurrences caused by the TR drive system were sub-divided into system component level in order to identify any underlying trends in the source of failures as shown in Figure 2-6. Overall, TR/ intermediate gearbox (28%) and TR drive shaft (26%) are the largest TR drive system causes. It can be seen that gearbox failures figure significantly for both the civil and military fleets, but shaft and coupling failures figure strongly only for the civil fleet and military fleet respectively. Such results can be skewed by recurring failures to certain aircraft types; the Bell 206 and Bell 47 account for a large proportion of the civil fleet drive shaft failures, and drive coupling failures were a problem with the military Sea Kings as identified in [4]. Fortunately, both these problem areas have now been identified and resolved but, nevertheless, the drive train is vulnerable to failure due to design weaknesses or poor material specifications, and this needs to be mitigated against in both current and future aircraft.

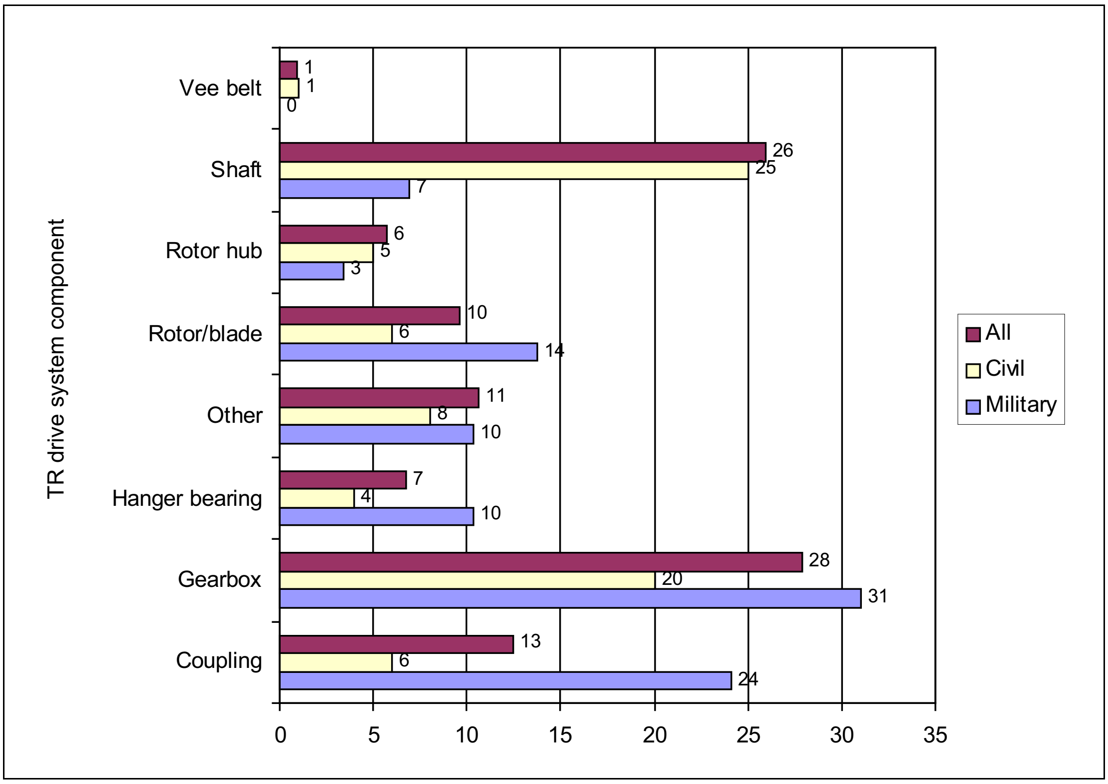

Figure 2-6 Components of TR drive system causes of TRF (all aircraft)

4.8 Cause comparison by fleet and category

The profiles for all heavy and light helicopter categories for the civil and military fleets are shown in Figure 2-7 and Figure 2-8 respectively. The overall cause profiles for the military and civilian fleets are similar with the largest cause being the TR drive system, followed by TR impact. This is somewhat surprising, given that the military and civilian fleets have different operational uses and hence are exposed to differing risks and parts of the operating envelope. For example, the military helicopter is required to spend more time in the hover (surveillance) and high power (dash transit) regimes than its civilian counterpart. Civilian helicopters are primarily used for the transport of personnel, hence the flight profile is designed to minimise the time spent in high-risk situations. The third highest cause for the civil fleet is an object hitting the tail, but this proportion is halved for the military fleet.

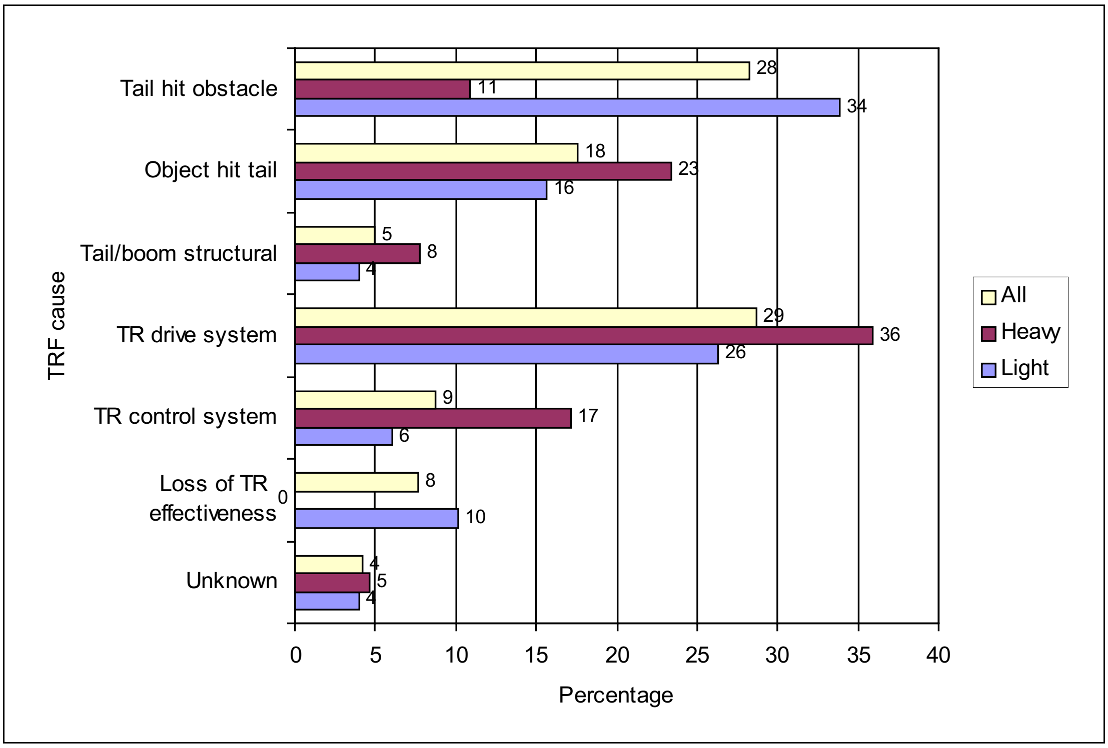

Figure 2-7 Distribution of TRF causes (civil aircraft)

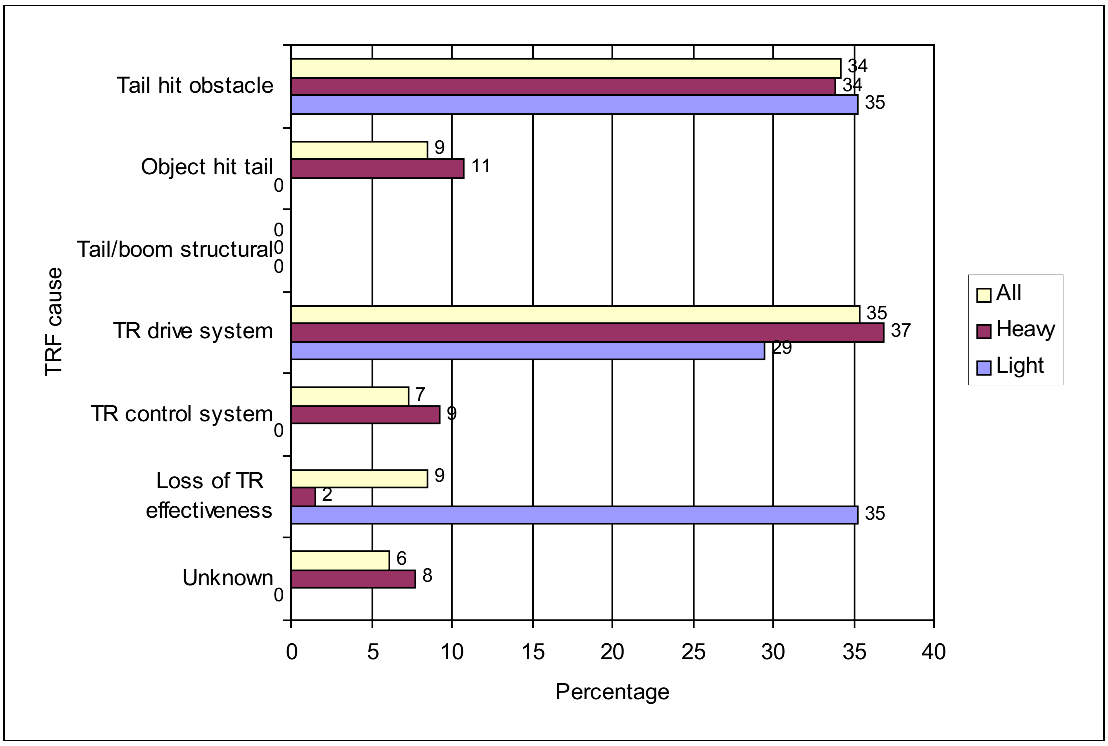

Figure 2-8 Distribution of TRF causes (military aircraft)

The proportion of military occurrences caused by the tail hitting an obstacle is high for both weight categories, most likely as a result of operations in confined spaces or at low altitude. It is postulated that the high civilian figure for the same cause of light category occurrences is attributable to the large number of such aircraft used for pilot training. Indeed, in this weight category, this cause even surpasses that of the TR drive system (which is higher for both military and civil heavy aircraft). The other cause which is similarly high for military aircraft, where there is only one type included (Gazelle), is loss of TR effectiveness.

A detailed comparison of the data for all fleets and types, including the US military, can be found in [10].

4.9 Comparison by phase of flight

The distribution of TRFs by phase of flight is important when considering mitigating technologies. Figure 2-9 shows that the largest number of TRF occurrences (27%) and fatalities (56%) occur during transit. This is consistent with the proportion of time that the aircraft spends in this single phase, and is therefore where greatest potential benefit could be gained from the application of mitigating technologies. Approximately two thirds of occurrences in this phase are caused almost equally by an object hitting the tail and TR drive system failure, and this phase is where control system failure and tail/boom structural failure causes also reach their maximum numbers. TR torque is typically higher in the hover, take-off and landing phases (where 51% of occurrences take place) when compared with the other phases of flight (41% of occurrences). The data given in [10] reveal that the proportions of occurrences caused by the tail drive are 48% for hover, take-off and landing to 42% for other known phases. For object hit tail and tail hit obstacle causes combined, the proportions are 55% for hover, take-off and landing and 36% for the other known phases. Thus, with respect to the relative duration spent in these phases, the high torque phases exhibit disproportionately large numbers of occurrences, including those caused by failure of the tail drive system, but particularly for tail/object impact. It would be expected that the tail drive is more likely to fail when providing high torque, and that there is a greater likelihood of tail impact when operating close to the ground.

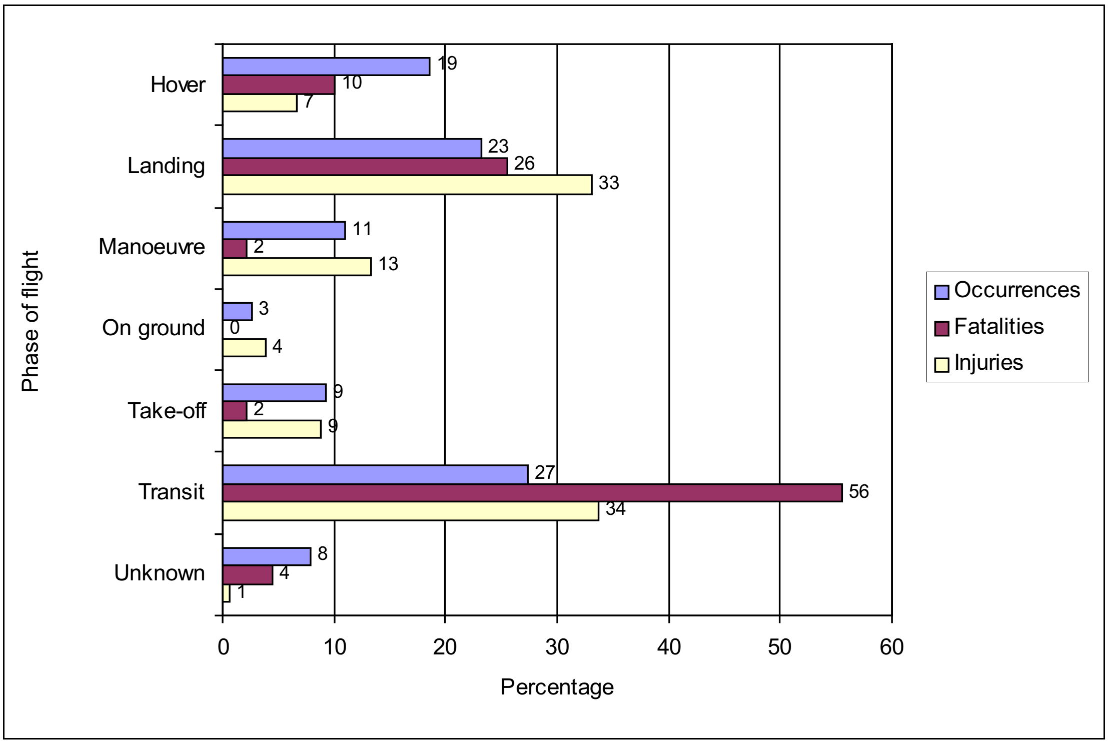

Figure 2-9 Distribution of TRFs by phase of flight (all aircraft)

4.10 Comparison by military type

The UK military occurrences by type are given in Table 2-9, by technical and operational causes as well as the total numbers of accidents and fatalities. A similar table for the period 1971 to 1994 was presented in the TRAC report; the present data are different due to the longer period covered and additional records that have been obtained. If the now out-of-date RN Wessex is ignored, the type most subject to failure is the Lynx (combined occurrence rate of 33.2) followed by Puma (24.0) and Sea King (22.8).

Table 2-9 UK MOD TRF occurrences by type

Type	Causes				Occurrences		Accidents		Fatalities	
	Technical		Operational							
Royal Navy										
Wessex	2	23.8	0	0.0	2	23.8	2	23.8	0	0.0
Sea King	13	17.0	6	7.8	19	24.8	16	20.9	0	0.0
Lynx	2	10.3	3	15.5	5	25.8	5	25.8	9	46.4
Gazelle	0	0.0	3	18.7	3	18.7	3	18.7	0	0.0
Royal Air Force										
Puma	6	18.0	2	6.0	8	24.0	7	21.0	3	9.0
Wessex	3	4.0	0	0.0	3	4.0	3	4.0	3	4.0
Sea King	1	6.4	1	6.4	2	12.7	1	6.4	0	0.0
Gazelle	0	0.0	3	14.2	3	14.2	3	14.2	0	0.0
Army										
Lynx	4	9.1	12	27.3	16	36.4	6	13.7	5	11.4
Gazelle	0	0.0	4	3.5	4	3.5	2	1.8	1	0.9
Key:	Number					Rate per million flying hours				

The data for the US Navy and Marine Corps are given in Table 2-10, where it can be seen that the AH-1 and SH-2 are predominant; all the SH-2 cases are of the most serious occurrence (known in the US as 'mishap') class. It should be noted that the cause was not known for every TR occurrence. Data for all additional military and civil types covered in the database, with causes, are provided in [10].

Figure 2-10 US Navy and Marine Corps TRF occurrences by type

Type	Causes				TR occurrences ('mishaps')							
	Technical		Operational		All		Class A		Class B		Class C	
AH-1J/T	0	0.0	3	11.7	5	19.5	2	7.8	1	3.9	2	7.8
UH/HH-1N	1	3.3	1	3.3	3	10.0	1	3.3	0	0.0	2	6.7
CH/MH/RH-53D/E	3	6.6	4	8.8	7	15.4	2	4.4	1	2.2	4	8.8
HH/SH-60B/F/H	2	2.3	4	4.6	7	8.0	2	2.3	2	2.3	3	3.4
SH/UH/VH-3D/H	0	0.0	2	5.7	3	8.5	1	2.8	1	2.8	1	2.8
SH-2F/G	1	6.4	2	12.9	3	19.3	3	19.3	0	0.0	0	0.0
Key:	Number					Rate per million flying hours						

5 Conclusions

Cross-references to the main text are given in parentheses.

5.1 The nature of TRFs

- Different levels of compensation will be required for each of the lost or degraded TR functions (torque reaction, directional stability and yaw control), depending on the phase of TRF management and control (transient, manoeuvre and landing) and the type of TRF. Primarily, it is the inherent response characteristics of the helicopter that determine the ability to provide compensation (2.1).
- For TRDFs, and TRCFs where the post-failure pitch angle of the TR blades is different from the pre-failure trim position, the immediate effect is a yaw response. The level of initial yaw acceleration will depend on the nature of the failure; the level of yaw rate and attitude build-up will depend on the forward speed. Typically, the higher the forward speed, the lower these transient excursions, although it should be noted that some aircraft exhibit directional stability reversals. The extent of such excursions and associated disorientation is critical to successful recovery (2.2).
- Once the initial TRF transients have been checked, the pilot’s next action will depend on the type of failure, the initial flight condition and aircraft type. Where possible however, the aircraft will be manoeuvred in heading, speed and altitude to prepare for landing. The pilot workload during the landing phase is very high, but aligning the aircraft with the flight path is arguably the most critical task in minimising loss of life and major airframe damage (2.3, 2.4).

5.2 The extent of TRFs

- A review by SAES-S revealed that some of the statistics quoted in the TRAC report were erroneous, including the total utilisation of the UK MOD fleet, and the accident classification used for the UK civil fleet. Consequently, the MOD rate of TRF occurrence due to technical causes was thus reduced from 13.8 to 9.1 per million flying hours, and the overall accident rate for civil aircraft was raised from 5.5 to 8.0 per million flying hours. The individual UK MOD type statistics stand as originally published. The ratios of internal to external causes of TRF were approximately 3:2 and 2:1 for the military and civil fleets respectively. The civil fleet statistics revealed the ratio of internally caused TRDFs (most likely due, but not limited to the TR drive system) to those of TRCFs (most likely due, but not limited to the TR control system) to be 3:1. Overall, the TRF accident rates for the UK fleets covered in the TRAC report were at least 8 times worse than the UK military requirement of 1 per million flying hours (4.2).
- The extended occurrence database containing 344 entries used the MOD Category 3-5 and MORS accident definitions for UK military and civil data respectively, whereas those from the US, Canada and New Zealand were classed by slightly different criteria. These differences in definitions, the classifications of causes and the data recorded made the use of data more difficult and the results less reliable than would have been the case if a common approach had been taken (4.4).
- The overall accident rates across the fleets were in the range 9.2 to 15.8 per million flying hours. There is a large variation in the accident rates for the heavy and light aircraft, due to the operational conditions and roles performed by the different classes. There are considerable variations in the rates by aircraft type, and there is no annual trend to suggest that rates will converge on a consistent figure (4.6).

- The largest causes of TRF are the TR either striking or being struck by an object which causes approximately one half of all TRF occurrences and fatalities, and failure of the TR drive system which causes approximately one third of all TRF occurrences and fatalities. The TR drive shaft, gearboxes and couplings are chiefly responsible for the latter, though there are significant differences in the proportions for the civil, military, heavy and light aircraft categories. It is clear, however, that the drive train is vulnerable to failure due to design weaknesses, poor material specifications and maintenance, and this needs to be mitigated against in both current and future aircraft (4.7).
- The largest number of TRF occurrences (27%) and fatalities (56%) occur during transit. This is consistent with the proportion of time that the aircraft spends in this single phase, and is therefore where greatest potential benefit could be gained from the application of mitigating technologies. Approximately two thirds of occurrences in this phase are caused almost equally by an object hitting the tail and TR drive system failure, and this phase is where control system failure and tail/boom structural failure causes also reach their maximum numbers. TR torque is typically higher in the hover, take-off and landing phases (where 51% of occurrences take place) when compared with the other phases of flight (41% of occurrences). The data given in [10] reveal that the proportions of occurrences caused by the tail drive are 48% for hover, take-off and landing to 42% for other known phases. For object hit tail and tail hit obstacle causes combined, the proportions are 55% for hover, take-off and landing and 36% for the other known phases. Thus, with respect to the relative duration spent in these phases, the high torque phases exhibit disproportionately large numbers of occurrences, including those caused by failure of the tail drive system, but particularly for tail/object impact. It would be expected that the tail drive is more likely to fail when providing high torque, and that there is a greater likelihood of tail impact when operating close to the ground (4.9).
- The UK MOD type most subject to failure is the Lynx (combined Service occurrence rate of 33.2 per million flying hours) but Puma (24.0) and Sea King (22.8) also stand out as exceeding the airworthiness design requirements by a dangerous margin. The AH-1 (19.5) and SH-2 (19.3) stand out most for the US Navy and Marine Corps (4.10).

6 Recommendations

Cross-references to the main text are given in parentheses.

- It is recommended that the relevant authorities co-operate to standardise accident and incident classifications, and the details recorded in occurrence reports world-wide in order to provide more robust comparison and ease future data analysis (4.4).

Section 3 Airworthiness design requirements

1 Introduction

The work reported on in this section covers objective 4 as defined in Section 1. A primary purpose of airworthiness requirements is to ensure that flight critical components, the failure of which would be catastrophic, are designed with an extremely remote probability of failure. This leads to a design philosophy which combines testing and a thorough analysis of failure modes and effects. A second consideration, particularly for military operations, concerns failures resulting from operational circumstances. If the likelihood of failure for operational reasons increases, then additional airworthiness requirements are necessary, particularly addressing the failure effects. In the context of airworthiness, TRs do not have a good record, as evidenced by the review in Section 2. This poor record and the desire on the part of the regulatory bodies for improvement is, of course, the motivation for the current study.

In this section, the adequacy of current rotorcraft civil Joint Aviation Requirements JAR-27 [2] and JAR-29 [3] (for small and large categories respectively) and the UK military Defence Standard 00-970 [1] is addressed in the following three ways. First, TR drive systems are considered in 2 and TR control system failures, in which the degree to which the requirements direct designers towards fault-tolerant controls, are discussed in 3. Second, comparison of these rotorcraft requirements is made, to the extent possible, with civil fixed-wing aircraft standards defined in JAR-25 [12], resulting in the identification of a regulatory gap. Third, regarding the dynamic response to TRFs, handling qualities criteria are identified in 4 that could serve as a means of quantification in a failure modes and effects analysis. Conclusions and recommendations from this section are presented in 5 and 6 respectively.

2 Airworthiness design requirements for tail rotor drive systems

Failures of TR drive systems represent a serious concern to operators and regulators, as highlighted by the data presented in Section 2. There appears to be no deficiency in the civil or defence design standards where the requirements for flight critical integrity are clearly stated. For example, in JAR-29, paragraph 547 requires a design assessment with failure analyses for the main rotor and TR structures and associated pitch control mechanisms. The Defence Standard contains a similar requirement, driving the designer to fault tolerant or extremely reliable simplex designs.

However, the occurrence analysis suggests that designs are not meeting the required integrity standard. With this state of affairs, four objectives are identified which echo the goals of the current programme:

a) A thorough review of the application of the principles of the design standards should be undertaken for all future designs. This should encompass:
   - the design cases;
   - expected utilisation in terms of flight conditions;
   - manoeuvres;
   - environmental conditions;
   - the different forms of pilot control action.

b) The application of technologies that can provide the pilot with advance warning of a failure or imminent failure, are strongly recommended (see Sections 4 and 6).

c) The development of technologies that mitigate against the severely adverse effects of TRDF (see Sections 5 and 6).

d) The production of type-specific advice to aircrew and the associated training requirements (see Sections 7 and 8).

The first of these emphasises the need to apply fully the regulatory intent of high reliability and failure tolerance in the design of helicopter TR drive systems. The remaining three relate to existing types or new types where the TR is vulnerable to damage or failure.

3 Airworthiness design requirements for tail rotor control systems

3.1 Résumé of the 'cost' of TRCFs

As described in Section 2, of the internal causes (which cause 42% of all TRF occurrences), 71% are attributed to the TR drive system and 20% to the TR control system. The latter cause has resulted in nearly 1.5 occurrences per year over the last 20 years, and the 'failure cost' of the current design philosophy regarding TR control systems is clearly high. This highlights that TR control system failures are not remote occurrences, and that changes to the airworthiness regulations could serve to steer manufacturers towards safer design solutions.

3.2 UK Defence Standard 00-970

The UK Defence Standard 00-970 Volume 2 [1] deals with rotorcraft. Book 1, Part 2 covers structural strength and design for flight; Chapter 203 relates to Control Systems – Mechanical Components. Paragraph 3.3 sets requirements for the failure immunity and safety of the control circuits:

> 'A failure mode and effects analysis shall be carried out on the control system, supported where necessary by tests. All combinations of potential failures and jamming shall be considered. The associated probabilities of occurrence shall be assessed in relation to the continued safe flight, and landing of the rotorcraft to levels stated in the relevant specification for the rotorcraft.'

The general requirement can be fulfilled either through redundancy or simplex integrity and it is the responsibility of the Project Director to specify the acceptable failure probability levels in the Rotorcraft Specification.

3.3 Joint Aviation Requirements JAR-27 and JAR-29

JAR-27 and JAR-29 are divided into Sub-Parts A-G, supported by Advisory Circular Joint (ACJ) sections describing acceptable means of compliance and interpretations. It is useful to review the relevance of each of the appropriate Sub-Parts to the airworthiness of flight controls relating to failure characteristics in general, and TRFs in particular. Note that some of the following observations only apply to JAR-29 and not to JAR-27.

- Sub-Part B (Flight) makes no reference to flight control characteristics in failed conditions. Only post-engine failure flight characteristics are considered.
- Sub-Part C (Strength) does not require flight control systems to be subjected to design assessment with failure analyses, unlike main rotor and TR structures and associated pitch control mechanisms (i.e. the rotating components in paragraph

547). The corresponding ACJ to paragraph 547 classifies failures according to severity - from minor to catastrophic. In the analysis of hazardous and catastrophic failures, the designer is required to substantiate the compensating provisions (e.g. design features, high level of integrity, flight limitations and emergency procedures) which are made available to minimise the likelihood of their occurrence.

- Sub-Part D (Design and Construction) makes no reference to failures except for stability augmentation systems (paragraph 672) and power boost or power-operated control systems, where the requirement is for redundancy to ensure that single failures are tolerable (paragraph 695). In contrast, paragraph 671 of JAR-25 requires that any single failure, or combination of failures, not shown to be extremely improbable, should not prevent continued safe flight and landing. Analysis and/or test must show compliance with this requirement. Interestingly, the UK's forerunner to JAR-27 and JAR-29 – British Civil Airworthiness Requirements (BCAR) 29 [13] – includes in paragraph 671 a more explicit requirement on the likelihood of failures in the primary flight control system:

  > 'The primary flight control system together with the trimming control system must be such that the likelihood of failure (including disconnection) of any element which could result in a dangerous measure of control being applied or lost at any speed up to V_{NO} is predicted to be – extremely improbable for Group A rotorcraft; and extremely remote for Group B rotorcraft.'

A specific requirement on the integrity of the flight control system appears to have been lost during the transition from BCAR to JAR. It should be noted, however, that BCAR were used for the certification of virtually all the types analysed in Section 2, and therefore the occurrence history would not have been affected by this lost requirement. In addition, although the military requirements appear to be far more rigorous than their civil counterparts, the military and civil occurrence rates are very similar.

- Sub-Part F (Equipment) presents the requirements for airworthiness of equipment under failed conditions. Paragraph 1309 requires that rotorcraft systems must be designed so that the occurrence of failures which are catastrophic (prevent continued safe flight and landing) are extremely improbable, and the occurrence of failures which are hazardous (reduced capability to cope with adverse operating conditions) are improbable. Compliance by analysis and test is required. Although this requirement is applicable to flight control systems, its interpretation in practice, due to the inability to avoid simplex systems on conventional helicopters, is less stringent than its text would imply.
- Sub-Part G (Operating Limitations and Information) refers, in paragraph 1517, to the requirement to establish the limiting height-speed envelope within which it is not possible to make a safe landing following power failure; no such requirement for TRFs is included.

<u>There is a regulatory gap regarding TR control systems – current designs are neither pushed, by regulations, towards fail-safe solutions through redundancy, nor to higher 'simplex' integrity through detailed design assessments.</u> It could be argued that if designs are allowed with a propensity to experience TRFs, then manufacturers should be encouraged to advise operators to minimise the time spent in areas of the flight envelope where the probability of a successful recovery from a TRF is low. A two-path solution to closing the civil regulatory gap is proposed as practicable and appropriate:

a) To require all practicable precautions to be taken to prevent single failures causing loss of continued safe flight and landing (i.e. require redundancy along the lines of that found in JAR25.671).

b) Where it is considered that redundant systems are impractical, to require justification of this and require that a design assessment be performed on the solution selected. This assessment shall include a detailed failure analysis to identify all failure modes that will prevent continued safe flight and landing and identification of the means provided to minimise the likelihood of their occurrence.

It is recommended that the JARs be amended to provide this two-path solution to closing the regulatory gap. In particular the JAR 29.671 should be revised to require the two-path approach as described above. The same advisory material as provided for JAR29.547, describing how a design assessment is performed, should be used.

Manufacturers should be required to analyse the effect of TRFs and, where these effects are significant, provide at least Type 2 validated aircrew advice. Where such advice is not provided, it is recommended that advisory operational restrictions be provided (similar to the H-V diagram for engine failures). Such restrictions could also be realised through the inclusion of a reference to flight control/handling characteristics following TRFs in Sub-Part B of JAR-27 and JAR-29.

4 Tail rotor failure handling criteria

4.1 Background

With TRs demonstrably not as reliable as the design standards require, an equally important airworthiness aspect relates to the ability of the aircrew to manage and control the helicopter following a TRF. The need for this aspect to be addressed is reinforced by the high proportion of TRFs (53%) from external and operational causes (e.g. TR colliding with an obstacle – see Section 2).

As discussed in Section 2, the management and control of a TRF can be assessed in three phases:

a) **Transient**: the failure transient and recovery to a safe flight condition.

b) **Manoeuvre**: manoeuvring in the failed condition.

c) **Landing**: the ability to perform a successful landing.

The ability of the aircrew to fly the aircraft within defined safety and performance standards within the three phases will depend on a number of key aspects. These include the aircraft configuration, the flight condition prior to failure (including speed and altitude), the pilot's attentiveness, training and skill, the TRF type and cues, and the response characteristics of the aircraft. The handling criteria proposed in this section refer to the response characteristics of the aircraft to the failure and ensuing pilot control inputs.

4.2 Recovery from the failure transient

The transient attitude excursions are critical to the pilot being able to achieve a successful recovery and feature as the primary response characteristics of interest in this investigation. In the handling qualities requirements standard ADS-33D [7], the allowable response transients following system failures are described in terms of handling qualities defined as Level 1, Level 2 and Level 3, where;

Level 1: Corresponds to good handling qualities that enable the pilot to achieve a desired level of performance, well within the margins of error for the mission task, and at a low workload, corresponding to no more than minimal control compensation.

Level 2: Corresponds to handling qualities with tolerable deficiencies that enable the pilot to achieve an adequate performance standard, just within the margins of mission task error, but possibly requiring extensive pilot compensation and hence high workload.

Level 3: Corresponds to handling qualities with major deficiencies that intrude significantly on the pilot's ability to achieve even an adequate performance standard for a mission task, with maximum tolerable compensation.

Handling qualities with such major deficiencies that the pilot is likely to lose control are referred to in this report as Level 4; it should be noted, however, that Level 4 is not defined or used by ADS-33D. These Levels encompass the Cooper-Harper Handling Qualities Ratings (HQRs) as described in [11] and shown in Figure 3-1.

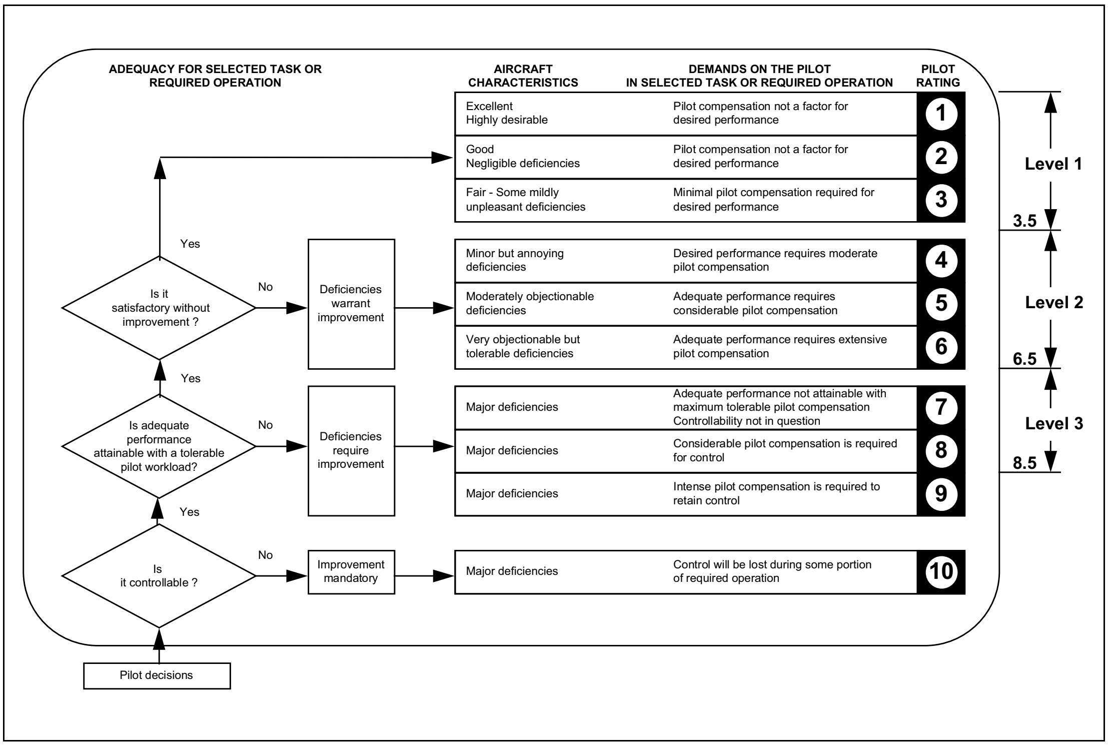

Figure 3-1 Cooper-Harper HQR scale

Table 3-1, taken from [7], gives the transient perturbation limits for rotorcraft without failure warning and cueing devices. This indicates that following a failure when in forward flight (>45 kn) and close to the ground:

If:

- the pilot takes no action for 3 seconds and
- the aircraft stays within the Operational Flight Envelope (OFE) and
- pitch, roll and yaw attitude excursions are between 10° and 24°; or translational accelerations are between 0.2 and 0.4g;

Then the aircraft will, at best, exhibit Level 3 handling qualities.

Table 3-1 ADS-33D failure transient limits

Level	Flight condition		
	Hover and low speed	Forward flight	
		Near-Earth	Up and away
1	3° roll, pitch and yaw. 0.05g n_x, n_y, and n_z. No recovery action for 3.0 sec.	Both hover & low speed & forward flight up & away requirements apply.	Stay within OFE. No recovery action for 10 sec.
2	10° attitude change or 0.2g acceleration. No recovery action for 3.0 sec.	Both hover & low speed & forward flight up & away requirements apply.	Stay within OFE. No recovery action for 5.0 sec.
3	24° attitude change or 0.4g acceleration. No recovery action for 3.0 sec	Both hover & low speed & forward flight up & away requirements apply.	Stay within OFE. No recovery action for 3.0 sec

The attitude and acceleration transient response criteria applicable to hover/low speed and near-Earth conditions are based on the aircraft displacement after 3 seconds without any pilot action; the aircraft would be displaced about 30 feet (10m) in all directions at the upper excursion limits. ADS-33D is a military standard and hence considers nap-of-the earth operations where tactical use is made of ground cover for stealth. When flying close to the ground and obstacles, such transient excursions are likely to result in a collision. In this study it is suggested that such criteria are equally applicable to civil helicopter operations close to the ground. For up-and-away forward flight conditions, the requirements are based solely on staying within the OFE.

Considering the flight critical nature of the TR function, it is suggested that the handling boundary of most relevance for both low level and up-and-away flight is that between Level 3 and Level 4. The criteria in Table 3-1 formed the starting point for developing desired and adequate performance standards for the piloted simulation described in Section 6. The pilot's task was to recover to a steady trim condition while staying within the OFE and defined spatial confines.

Regarding TRFs in the low hover, the pilot has no option but to try to land as quickly as possible. Descending vertically and attempting to cancel the yaw motion, the three failure phases tend to merge into one with the pilot attempting to cushion a vertical descent. In the case of TRCFs, a degree of yaw suppression can be achieved using the rotor speed controls if available. In the Lynx flight trials [5] it was found that an 11% increase in rotor speed was sufficient to arrest the rate of yaw following a LP TRCF (c.f. RNAS Portland Lynx TRCF in 1998 [14]). In the case of a TRDF in the hover, the strategy will depend on the initial hover height. Close to the ground, the pilot may prefer to accept a yaw rate rather than a (very) heavy landing and hence not shut down the engines. However, the Lynx is unique in having a single Speed Select Lever (SSL) controlling the main rotor speed; all other twin engine helicopters have either twin SSLs or twin throttles.

From a higher hover, from which a safe transition into autorotation is theoretically possible, settling into autorotation and shutting down the engines or transitioning into forward flight may be the preferred strategy. However, the Lynx trial indicated that a height loss of 2000 ft could be expected before the pilot regains sufficient control that an engines-off landing could be attempted. The main problem facing the pilot is how to maintain orientation and keep the aircraft attitude level while the flat spin is initially controlled and then reduced to zero. The most appropriate option in this situation would be to completely relieve the pilot from the attitude holding task; such handling is best provided by an attitude command, attitude hold (ACAH) control system. The potential benefits of pitch/roll ACAH response type, as opposed to a rate command response type, were explored in the AFS trial described in Section 6.

4.3 Manoeuvrability in the failed condition

Having recovered from the failure, the pilot's next action will depend on the type of failure and the initial flight condition. As discussed in Section 2, from a forward flight initial condition at cruise altitude, for example, the pilot will generally want to be able to accomplish two things:

a) Manoeuvre the aircraft to change heading, speed and altitude, including flying the aircraft into a flight condition for an approach to a landing.

b) If possible, find a power/speed combination for continued flight giving time to select a safe landing area. The ability to carry this out will depend upon the vehicle’s inherent stability and the type of TRF, although there are some types where there is no acceptable power/speed combination, and an immediate autorotative landing is the only possibility.

With a TRDF, the pilot may or may not be able to manoeuvre the aircraft in a power-on state without risking loss of control and, for safe flight, it may be necessary to shut the engines down. The critical response that determines the capability to manoeuvre with power on will be the yaw response to collective. The requirements are described in [7] paragraph 3.3.9.1, in terms of the ratio of yaw rate to height rate response and are illustrated in Figure 3-2.

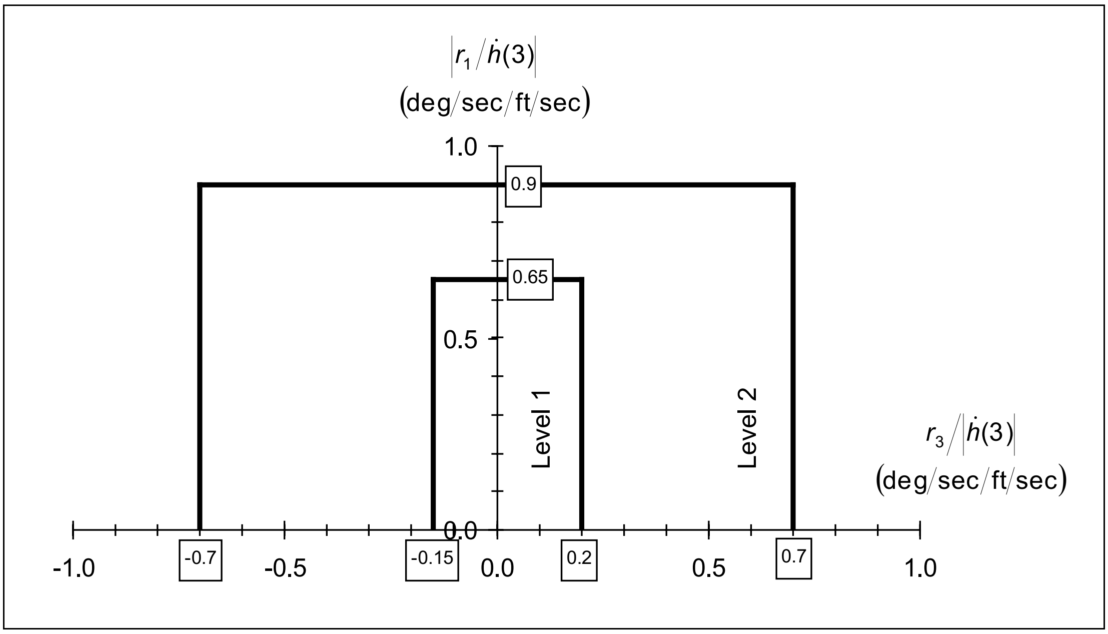

Figure 3-2 ADS-33D collective to yaw coupling requirements

Where:

- $r(t)$ and $\dot{h}(t)$ are the yaw and height rate responses respectively at t seconds following a step input at 0 seconds;
- r_1 is the first (or largest magnitude if more then one) yaw rate peak before 3 seconds or $r(1)$ if no peak occurs before then;
- r_3 is $(r(3)-r_1)$ and $(r_1-r(3))$ for positive and negative r_1 respectively.

Note that there is no reference to Level 3.

In terms of general manoeuvrability, the ability to turn on cyclic without losing control is characterised by the turn co-ordination criteria of [7], paragraph 3.4.6.2. This is illustrated in Figure 3-3 where the criteria are expressed in terms of the ratio of sideslip to roll attitude following a control input designed to generate a step change in aircraft attitude.

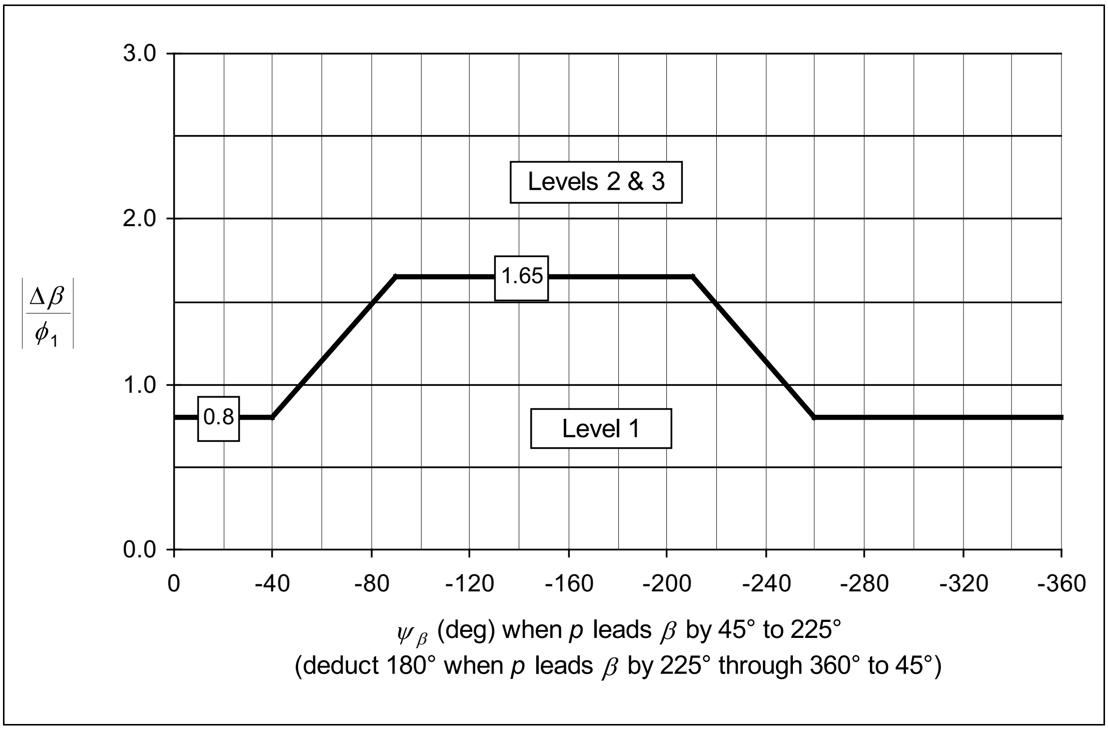

Figure 3-3 ADS-33D sideslip excursion limitations

Where, in response to an abrupt lateral control demand:

- β and p are sideslip angle and roll rate respectively;
- ϕ_1 is the initial peak magnitude in roll response;
- $\Delta\beta$ is the maximum change in sideslip angle;
- ψ_β is a phase angle expressed as a lag for a cosine representation of the lateral-directional oscillation in sideslip.

Note that Level 2 and Level 3 are treated together.

4.4 Landing

As discussed in Section 2, the landing task is a complex combination of four tasks where the pilot is required to:

a) conduct a final deceleration to the required landing speed;

b) flare the aircraft while arresting the rate of descent with collective;

c) yaw the aircraft to line up with the flight path; and

d) level the attitude just prior to touch down.

Most of these actions are critical to a successful landing, but aligning the aircraft with the flight path is arguably the most critical both in terms of minimising the risk of roll-over and also because this is the one axis over which the pilot no longer has direct control. The pilot workload in this phase of the action will be a result of the need to co-ordinate four different actions within a few seconds, particularly the co-ordination of height rate and yaw response.

It is recommended that the ADS-33D failure transient limits, collective to yaw requirements and sideslip excursion limitations are used as a means of quantification in the failure modes and effects analysis, as part of the two-path solution described earlier in this section.

Handling qualities with a failed TR are severely degraded. Key parameters which affect aircraft handling in such failure conditions include yaw stiffness and yaw damping. Technologies which exploit improved stiffness and damping to mitigate against TRFs are discussed in Sections 5 and 6 and it is recommended that manufacturers explore the potential of these systems for providing improved handling.

5 Conclusions

Cross-references to the main text are given in parentheses.

- Four objectives have been identified in the design requirements for TR drive systems which echo the goals of the current programme. The first of these emphasises the need to apply fully the regulatory intent of high reliability and failure tolerance in the design of helicopter TR drive systems. The remaining three relate to existing types or new types where the TR is vulnerable to damage or failure (2).
- A regulatory gap has been identified in JAR-27 and JAR-29 relating to TR control system failures – current designs are neither pushed, by regulation, towards fail-safe solutions through redundancy, nor to higher ‘simplex’ integrity through detailed design assessments. A two-path solution is therefore proposed as practicable and appropriate (3.3):

a) To require all practicable precautions to be taken to prevent single failures causing loss of continued safe flight and landing (i.e. require redundancy along the lines of that found in JAR25.671).

b) Where it is considered that redundant systems are impractical, to require justification of this and require that a design assessment be performed on the solution selected. This assessment shall include a detailed failure analysis to identify all failure modes that will prevent continued safe flight and landing, and identification of the means provided to minimise the likelihood of their occurrence.

- With TRs demonstrably not as reliable as the design standards require, an equally important airworthiness aspect relates to the ability of the aircrew to manage and control the helicopter following a TRF. Handling qualities with a failed TR are severely degraded. Key parameters which affect aircraft handling in such failure conditions include residual yaw stiffness and yaw damping. Technologies which exploit improved stiffness and damping to mitigate against TRFs are discussed in Sections 5 and 6 (4.1, 4.4).

6 Recommendations

Cross-references to the main text are given in parentheses.

- It is recommended that the JARs be amended to provide the two-path solution to closing the regulatory gap. In particular the JAR 29.671 should be revised to require the two-path approach as described in 5. The same advisory material as provided for JAR29.547, describing how a design assessment is performed, should be used (3.3).
- It is recommended that the ADS-33D failure transient limits, collective to yaw requirements and sideslip excursion limitations are used as a means of quantification in the failure modes and effects analysis, as part of the two-path solution (3.3).
- Manufacturers should be required to analyse the effect of TRFs and, where these effects are significant, provide at least Type 2 validated aircrew advice. Where such advice is not provided, it is recommended that advisory operational restrictions be provided (similar to the H-V diagram for engine failures). Such restrictions could also be realised through the inclusion of a reference to flight control/handling characteristics following TRFs in Sub-Part B of JAR-27 and JAR-29 (3.3).
- Handling qualities with a failed tail rotor are severely degraded. It is recommended that the airworthiness requirement authorities establish the residual yaw stiffness and damping which should be available after TRFs. It is recommended that manufacturers explore the potential of technologies which exploit improved stiffness and damping to mitigate against TRFs by providing improved handling (4.1, 4.4).

Section 4 Prevention and mitigation of TRFs using HUMS technology

1 Introduction

The work reported on in this section was performed by Smiths Aerospace Electronic Systems - Southampton (SAES-S, part of the Smiths Group) [10] and, together with the work reported on in Sections 5 and 6, covers objectives 2 and 3 as defined in Section 1. The application of a HUMS to TRFs is described generally in 2 and current, future and other systems which may be beneficial in preventing TRFs are described in 3. The estimated benefits of these systems, and considerations for certification and presentation of in-flight information are described in 4. Summary conclusions and recommendations are provided in 5 and 6 respectively.

2 The application of Health and Usage Monitoring Systems

A HUMS could have an impact on TR occurrences in 2 ways:

a) Preventing the occurrence from taking place by providing a timely warning of any developing damage in the TR drive or control systems. Where a warning is possible, this should enable maintenance intervention to detect the damage and prevent the flight from taking place, or provide timely information to the pilot to enable the flight to be terminated before a failure occurs.

b) Where a HUMS cannot provide any warning (prediction) of a failure, it could still have an important role to play in assisting the crew to diagnose the failure and determine the appropriate response. The key to successful handling of a TRF lies in the crew's ability to quickly recognise the type of malfunction and to select the proper emergency procedure. An HHMAG (Helicopter Health Monitoring Advisory Group) Working Group on flight deck health monitoring indications [15] did not recommended the use of existing HUMS to provide alerts (due to unacceptable false alarm rates), but did recommend their use to provide supplementary data.

Potential HUMS requirements can be defined in terms of the required monitoring and diagnostic functions, and the method of communication of information from these functions to maintenance personnel on the ground and/or to the crew on board the aircraft.

3 Monitoring and diagnostic functions

The functional requirements were identified from the analysis of occurrences described in appendix A. These are separated into requirements that can be met by current HUMS and those which could be met by development of the current HUMS. For each of the functions considered, the following tables describe the purpose and operation of the function, possible information to be presented to aircrew, and the categories of failures which the functions may be able to prevent or mitigate.

3.1 Functions provided by current HUMS

Those functions that could be provided by current HUMS are described in Table 4-1 to Table 4-5.

Table 4-1 TR drive shaft vibration monitoring

TR drive shaft vibration monitoring	
Purpose:	Warning to maintenance personnel.
Function:	Periodic vibration analysis to identify any increase in TR drive shaft vibration to warn of developing shaft and/or coupling failures.
Failure categories:	TRDF: TR drive shaft TR drive shaft spline coupling TR drive shaft Thomas coupling TR drive shaft tail fold disconnect coupling

Table 4-2 TR drive shaft hanger bearing vibration monitoring

TR drive shaft hanger bearing vibration monitoring	
Purpose:	Warning to maintenance personnel.
Function:	Periodic vibration analysis to identify any increase in TR drive shaft hanger bearing vibration to warn of developing bearing failures.
Failure categories:	TRDF: TR drive shaft hanger bearing

Table 4-3 Intermediate and TR gearbox vibration monitoring

Intermediate and TR gearbox vibration monitoring	
Purpose:	Warning to maintenance personnel.
Function:	Periodic vibration analysis to detect developing failures of the internal components of the intermediate and TR gearboxes.
Failure categories:	TRDF: Intermediate or TR gearbox TR gearbox mounting

Table 4-4 TR vibration monitoring

TR vibration monitoring	
Purpose:	Warning to maintenance personnel.
Function:	Periodic vibration analysis to identify any increase in TR vibration to warn of developing failures within the TR.
Failure categories:	Failure of the tail pylon structure. TRDF: TR gearbox mounting TR hub components TR blade failure

Table 4-5 Airframe vibration monitoring

Airframe vibration monitoring	
Purpose:	Warning to maintenance personnel.
Function:	Periodic vibration analysis to identify anomalous vibration and draw attention to abnormalities in the airframe structure or attachments.
Failure categories:	Failure of the tail pylon structure. Object hit tail – loose panels.

3.2 Functions requiring HUMS development

Those functions that could be provided subject to HUMS development are described in Table 4-6 to Table 4-14.

Table 4-6 Cockpit indication for vibration monitoring functions

Cockpit indication for vibration monitoring functions	
Purpose:	Pre-failure warning to aircrew.
Function:	Periodic vibration analyses. All data analyses would need to be performed in the on-aircraft system.
Crew information:	Cockpit indications would be provided for all the functions to enable warnings to be given to the aircrew during flight.
Failure categories:	As per specific vibration monitoring.

Table 4-7 Gearbox and bearing temperature monitoring

Gearbox and bearing temperature monitoring	
Purpose:	Pre-failure warning to maintenance personnel and aircrew.
Function:	Monitoring of temperature of TR drive shaft hanger bearings and the intermediate and TR gearboxes (assuming no monitoring is currently provided). This would require the fitting of temperature sensors to the monitored components. Vibration monitoring functions are, however, the preferred methods of monitoring these components.
Crew information:	Cockpit indications could be provided to give a high gearbox or bearing temperature warning to aircrew during flight.
Failure categories:	TRDF: TR drive shaft hanger bearing Intermediate or TR gearbox

Table 4-8 On-demand vibration checks

On-demand vibration checks	
Purpose:	Post-failure diagnostic information to aircrew.
Function:	Provision of on-demand checks of MR and TR vibration and display the results in the cockpit. Current HUM systems provide an on-demand capability for the gathering of MR and TR track and balance data but the results are not displayed on the aircraft.
Crew information:	The crew could be informed of the level of the current MR and TR vibration in order to determine the source of any perceived increase. Repeated use of the function could indicate whether this vibration is becoming progressively worse.
Failure categories:	An object hit the TR. Failure of the tail pylon structure. TRDF: TR gearbox mounting TR hub components TR blade failure

Table 4-9 Continuous rotor vibration monitoring

Continuous rotor vibration monitoring	
Purpose:	Post-failure warning/diagnostic information to aircrew.
Function:	Monitoring and continual cockpit display of MR and TR vibration as an alternative to the on-demand checks. In the absence of an on-demand measurement capability, continuous monitoring would be required to provide a timely indication.
Crew information:	The crew could be informed of the level of the current MR and TR vibration in order to determine the source of any perceived increase.
Failure categories:	An object hit the TR. Failure of the tail pylon structure. TRDF: TR gearbox mounting TR hub components TR blade failure

Table 4-10 TR rotational speed monitoring

TR rotational speed monitoring	
Purpose:	Post-failure warning/diagnostic information to aircrew.
Function:	Measurement of MR and TR rotational speed at a typical rate of 10 Hz, computation of frequency ratio and provision of a warning of TRDF when this ratio departs from that determined by the MR/TR drive gear ratio. The HUMS tachometer provided for TR balancing could be used for this function.
Crew information:	The crew could be warned of a TRDF following any deviation in TR rotational speed from that predicted based on MR speed. This would also obviate the need for the crew to discriminate between TRDFs and TRCFs.
Failure categories:	An object hit the TR. TRDF: TR drive shaft TR drive shaft spline coupling TR drive shaft Thomas coupling TR drive shaft tail fold disconnect coupling TR drive shaft hanger bearing Intermediate or TR gearbox

Table 4-11 TR control input/output monitoring

TR control input/output monitoring	
Purpose:	Post-failure warning/diagnostic information to aircrew.
Function:	Monitoring of both the TR control input (i.e. TR pedal position) and the control output (i.e. TR pitch) to detect deviations in the expected input/output relationship due to a TRCF. This would require an additional sensor to be attached to the TR pitch change mechanism to provide a direct measurement of TR pitch.
Crew information:	The crew would be warned of any detected TRCF. In addition, information on whether there was a consequent loss or increase of TR thrust could prompt the aircrew to make the correct response.
Failure categories:	Loss of TR effectiveness. TRCF: TR control system seized/jammed TR pitch change mechanism failure

Table 4-12 TR control mapping against flight parameters

TR control mapping against flight parameters	
Purpose:	Post-failure warning/diagnostic information to aircrew.
Function:	TRCF diagnosis via control out-of-range detection and TR rotational speed monitoring, as an alternative to TR control input/output monitoring. The range would be obtained by mapping TR and cyclic control inputs to aircraft flight regime parameters. The function may be able to utilise the control input signals currently acquired by the HUMS and recorded on the ADR/FDR. This approach has the advantage of removing the requirement for an additional sensor to directly measure TR pitch.
Crew information:	The crew would be warned of any detected TRCF. In addition, information on whether there was a consequent loss or increase of TR thrust could prompt the aircrew to make the correct response.
Failure categories:	Loss of TR effectiveness. TRCF: TR control system seized/jammed TR pitch change mechanism failure

Table 4-13 TR drive torque monitoring

TR drive torque monitoring	
Purpose:	Post-failure warning/diagnostic information to aircrew.
Function:	Monitoring of TR torque. This would be monitored at a typical rate of 10 Hz, and a total loss of torque would provide the same TRDF information as TR rotational speed monitoring. Mapping torque against control positions and aircraft flight regime parameters could also indicate a TRCF. The necessity of fitting a torquemeter in the TR drive system makes this a non-preferred option.
Crew information:	The aircrew would be warned of a TRDF or TRCF, and, in the event of a TRCF, could be given the information to prompt them to make the correct response.
Failure categories:	An object hit the TR. Loss of TR effectiveness TRDF: TR drive shaft TR drive shaft spline coupling TR drive shaft Thomas coupling TR drive shaft tail fold disconnect coupling TR drive shaft hanger bearing Intermediate or TR gearbox TRCF: TR control system seized/jammed TR pitch change mechanism failure

Table 4-14 Gearbox oil level sensing

Gearbox oil level sensing	
Purpose:	Warning to maintenance personnel and optionally to aircrew.
Function:	Monitoring of intermediate and TR gearbox oil levels, providing a back-up to the current oil level checks using gearbox sight glasses. This would require fitting of oil level sensors to the intermediate and TR gearboxes. Sensors could be optical, capacitative, float or hot wire devices. An optical system is in service on the EH-101, which automatically checks gearbox oil levels on power-up prior to rotor start. The potential requirement for gearbox modifications to accommodate the sensors may make this function impractical to retrofit to existing aircraft.
Crew information:	A cockpit indication could be provided to give low gearbox oil level warning to the aircrew prior to flight.
Failure categories:	Inadequate oil in the gearbox.

3.3 Other monitoring technology

The technology described in Table 4-15 would probably be implemented separately from HUMS, but might be considered as a candidate for integration into new generation HUMS with expanded capabilities. Such integration would, however, be expected to require suitably partitioned hardware and software.

Table 4-15 TR tip strike warning

TR tip strike warning	
Purpose:	Warning to aircrew.
Function:	Warning of pre-defined proximity of TR to obstacles. An active laser scanning device could be used to detect obstacles and provide an output to aircrew via a suitable cockpit display.
Crew information:	The crew could be warned of the presence of the obstacle and be given its bearing to enable the necessary avoiding action to be taken.
Failure categories:	The TR hit an object.

4 Benefits and considerations

4.1 Estimated HUMS benefits

As reported by SAES-S [10], a detailed analysis was carried out on 31 occurrences (see appendix A) to estimate the potential benefits of HUMS for each of the TRF cause types for all of the 344 occurrences included in the database (see Section 2). Although the sample was representative, only 10% of the database occurrences were thus studied in detail, and this should be borne in mind. As with any analysis of occurrence data, it was hampered by lack of information available from accident/ incident reports on the precise circumstances, and sequence and timing of events. In a number of instances it was not possible to claim with confidence that a HUMS should have prevented an occurrence, but only that it might have done. The analysis was centred on the capability (or not) of HUMS to prevent or mitigate occurrences for each TRF cause, and estimation of HUMS detection effectiveness (coupled with general experience). The estimated benefits shown in Table 4-16 are based on judgements used to extrapolate the conclusions from the detailed analysis to all of the database occurrences, applied only to the proportion of cases judged to be HUMS-relevant. All estimates are conservative, but assume that the HUMS is correctly designed, installed and operated.

Table 4-16 HUMS benefits

Cause	Occurrences		HUMS detection effectiveness (%)		Occurrence effects No. (%)		Fatality effects
	Total	**HUMS relevant**	**Current**	**Dev.**	**Avoided**	**Mitigated**	**Avoided**
Tail hit obstacle	102						
Object hit tail	53	17	25		4 (1)		2
Tail/boom structural	13	7	50		4 (1)		1
TR drive system:	104						20
Current HUMS		73	70		51 (15)		
Dev. HUMS (avoid)		24		50	12 (3)		
Dev. HUMS (mitigate)		7		50		4 (1)	
TR control system	29	8	50		4 (1)		
Lost TR effectiveness	27	0			0		
Unknown	16						
Total	344	136			75 (22)	4 (1)	23

4.1.1 **Object hit tail**: The relevant HUMS technology that could warn maintainers of loose panels is airframe vibration monitoring. Other monitoring techniques assessed indicate no effect on the outcome of the occurrences. The identification of all loose panels not identified by pre-flight visual inspection is unlikely. The current HUMS, rated as 25% effective, applied to 50% of the database FOD occurrences (i.e. assumed to be caused by loose panels), thus prevents 1% of all TRF occurrences.

4.1.2 **Tail/boom structural failure**: The HUMS technology would affect this cause group through TR and airframe vibration monitoring providing maintenance warnings. The current HUMS, rated as 50% effective, applied to 50% of database structural failures, thus prevents 1% of all TRF occurrences.

4.1.3 **TR drive system failure**: The HUMS technology would affect this cause group through TR drive transmission vibration monitoring providing maintenance warnings and with HUMS developments, new monitoring functions and the provision of in-flight warnings to aircrew. The current HUMS functions are rated at 70% effectiveness (based on CAA analysis of current HUMS performance). The HUMS developments are rated at 50% effectiveness on the basis that these will be less mature. It is estimated that current HUMS would have prevented 49% of all TRFs caused by failure of the TR drive system, and 15% of TRFs overall. In addition, a development of the existing HUMS technology would have prevented or mitigated a further 15% of TRFs caused by failure of the TR drive system, and 4% of TRFs overall.

4.1.4 **TR control system failure**: The HUMS technology would affect this cause group through TR drive transmission vibration monitoring providing maintenance warnings of pitch control mechanism failures. The current HUMS is rated at 50% effectiveness applied only to the pitch control mechanism failures thus preventing 1% of all TRFs.

Other monitoring techniques assessed indicate no effect on the outcome of the TRFs.

4.1.5 **Loss of TR effectiveness**: The HUMS technology would not affect this cause group.

4.1.6 **TR hit an obstacle**: The only new technology proposed is a scanning laser tip strike warning system that would draw the pilot's attention to the actual position of an obstacle. This may help avoid occurrences if the pilot can react appropriately - in the occurrence scenarios involving training or aggressive manoeuvring he may already be workload limited. However, reliance upon such a device would have to be balanced against the possibility of system failure and resultant impact. The effectiveness of this technology in helicopters is so far unproven, but if rated at 25%, it could have prevented 8% of all TRFs.

4.1.7 **Overall effectiveness**: Note that of the 344 occurrences, it is estimated that 269 (78%) would not have been affected by current or developed HUMS.

4.2 In-flight information requirements

The requirements and concerns raised by pilots, accident investigators, manufacturers and airworthiness authorities are summarised as follows:

- There is a danger of swamping pilots with information.
- Post-failure warnings would be useful in order to distinguish between TRDF and TRCF. The frequency of TRFs exceeds existing requirements by a dangerous margin (see Section 2) but is a rare event and will not be uppermost in the mind of the pilot when it occurs. The pilot intervention time (PIT) is highly variable.
- Warnings of TRCF or TRDF should be accompanied by the required action, e.g. raise/lower collective for a TRCF giving increased/decreased thrust. The required action will be type-specific and may vary with flight conditions. This depends heavily on the yaw stiffness of the aircraft without TR thrust. For example, the Gazelle, Squirrel, Jetranger, Sea King and Wessex are relatively stable, whereas the Lynx and Puma are relatively unstable. Pilots may also need to know if the tail fin is damaged – the performance of the fin is important in deciding if a run-on landing is appropriate.
- The crew should be able to request information such as: TR speed (as a ratio to N_R), TR torque, vibration (bR and 1T, where b is the number of MR blades) or gearbox/bearing temperature. The pilot is always more confident if corroborative evidence is provided, i.e. two independent indications pointing to a problem.
- Information needs to be available on demand and without delay – so monitoring should be continuous.
- Pilots would like a trend of vibration/temperature to allow a comparison against normal conditions. This is to help reject spurious indications and to improve the detection of abnormalities. The flight manual limits are set wide to encompass all aircraft for all operations. Pilots recognise that the 'normal' values of temperature and vibration are often specific to an individual aircraft and its operation.
- Prediction of failures is desirable. Early indication of an abnormality would enable the pilot to choose the most benign flight state for maintaining control should a failure occur and to put out a PAN call.
- False alert rates are a concern. The results of the 1998/9 HHMAG Working Group study into flight deck indications recommended that HUMS vibration flight deck alerts should not be introduced until acceptable false alarm rates can be achieved, and that in the meantime any such monitoring indications organisations wish to pursue be designed as 'supplementary data' rather than 'alerts'. The false alert rate

for a warning should be considered in the hazard analysis for the aircraft since a warning may lead to a ditching followed by injury or death. In setting a target for the false alert rate, the hazard analysis should recognise that TR drive component failure rates are of the order of 1 per million flying hours [10]. This may require the HUMS to perform integrity checking of sensor data and to use corroboration between independent indicators. Evidence collected by the Air Accidents Investigation Branch (AAIB) suggests that once a failure has occurred there is gross vibration – so thresholds could be set high to avoid false alerts. This could be linked to a change/trend.

4.3 Certification

The safety certification of a HUMS is based on a safety case that includes the hazard assessment covering the potential for the HUMS functions to give misleading information and the consequences of this. Such an assessment would have to be done for each aircraft type so a generic case cannot be defined. As the level of certification increases, the costs of producing a system increase dramatically. Some guidelines resulting from discussions with the CAA are given in the following:

- The level of safety criticality depends on:
  - what the HUMS displays to the pilot;
  - what the pilot is expected to do;
  - the possible consequences of that action.

System criticality will be determined by the worst result produced from this analysis. Software Levels referred in the following are defined in [16].

- If the HUMS prompts the pilot to take an action which is in itself hazardous, then Level A software (function failure resulting in catastrophic failure condition) is required. An example of this would be a ditching, when the action could result in injuries or fatalities regardless of whether the HUMS prompt is correct or not. If the HUMS prompt is incorrect, the system would expose the aircraft and/or its occupants to unnecessary risk.
- If the HUMS prompts the pilot and distracts him during a potentially hazardous situation Level B software (function failure resulting in hazardous/severe-major failure condition) is required.
- If the HUMS information is only made available on pilot request, and the information would not require the pilot to do something that is potentially catastrophic, Level C software (function failure resulting in major failure condition) is required. An example is the pilot requesting corroborating evidence of vibration to confirm if it is 4R or 1T.

5 Conclusions

Cross-references to the main text are given in parentheses.

- Based on analysis of the occurrence database (described in Section 2), conservative estimates are that 49% of TRFs caused by failure of the TR drive system and 18% of TRFs overall could have been prevented by current HUMS. This is achieved primarily through monitoring of the TR drive system using current HUMS technology as a maintenance aid.
- In addition, a development of the existing HUMS technology would have prevented or mitigated a further 15% of TRFs caused by failure of the TR drive

system, and 5% of TRFs overall. The relatively low overall figures attributed to a developed HUMS is consistent with a detailed analysis of occurrences and aircrew comment; in most cases, where information could be given in flight it is not possible to show that the outcome of the occurrence would have been improved. flight deck indications that HUMS as 'supplementary data' 'alerts'. Any indication provided must be associated with unequivocal crew action (4.1.3, 4.2).

- The use of current and developed HUMS technologies alone will not bring the occurrence rate to an acceptable level; 78% of TRFs are unlikely to be prevented by HUMS and are caused predominantly through the TR striking, or being struck by an object (see Section 2). Other means are required to help avoid hazards, make the TR system less susceptible to damage and maximise the chances of a pilot successfully dealing with a failure that occurs in flight (4.1.7).
- Another technology proposed is a scanning laser tip strike warning system that would draw the pilot's attention to the actual position of an obstacle. This may help avoid occurrences if the pilot can react appropriately - in the occurrence scenarios involving training or aggressive manoeuvring the pilot may already be workload limited. However, reliance upon such a device would have to be balanced against the possibility of system failure and resultant impact. The effectiveness of this technology in helicopters is so far unproven, but could have prevented a further 8% of all TRF occurrences (4.1.6).

6 Recommendations

Cross-references to the main text are given in parentheses.

- Where HUMS are currently fitted, the fault detection capability of the HUMS should be fully exploited, and operators should develop effective procedures for use in conjunction with the system so that HUMS information is acted on in a correct and timely manner [17].
- <u>The fitting of appropriately designed HUMS, focussed on (but not limited to) monitoring TR drive system failure is strongly recommended.</u>
- <u>Action should be taken to further define the HUMS required for specific types or categories of helicopter. This should take into account the specific failure types, the handling qualities of the aircraft post-failure and economic factors.</u>
- Automated tools to assist in the examination of data collected by the current HUMS, and in the identification of potential fault-related trends should be improved.
- Although it cannot be justified purely on the basis of the numerical analysis, it is recommended that, in the longer term, consideration should be given to an intelligent cockpit warning system that prioritises warnings, presents immediate actions, guides the pilot through a sequence of steps, and makes supporting information available (4.2).
- Again, although it cannot be justified purely on the basis of the numerical analysis, it is recommended that further work be conducted to define an approach for the presentation of in-flight information. It should be emphasised that, as a result of the 1998/9 HHMAG Working Group on flight deck health monitoring indications, HUMS vibration flight deck alerts were not recommended to be introduced until acceptable false alarm rates can be achieved (4.2).
- Work should be undertaken to evaluate the merits of the new technology for rotor tip strike warning to reduce occurrences where the TR hits an obstacle.

Section 5 Prevention and mitigation of TRFs using non-HUMS technologies

1 Introduction

The work reported on in this section was performed by Westland Helicopters Limited (WHL, part of AgustaWestland) [18] and, together with the work reported on in Sections 4 and 6, covers objectives 2 and 3 as defined in Section 1. Technologies for preventing and mitigating the effects of TRFs are described in 2, and their utility are discussed in 3. Comparison of the sideforce and yaw moments provided by the TR, fin and a drag parachute is made in 4. Analysis of the benefits of the various technologies is made in 5 and summary conclusions and recommendations are provided in 6 and 7 respectively.

A review of prevention and mitigation technologies was undertaken using sources from the following literature searches:

- NASA (National Aeronautics and Space Administration) technical reports using the NASA Technical Reports Server on the Internet;
- AGARD and STAR publications; and
- patent applications using the WHL patent section.

The search of the above publications generated little information about TR control technology concepts currently under investigation by other manufacturers. The following concepts were identified for investigation:

- drag chute;
- inflatable fin;
- Spring Bias Unit/Negative Force Gradient spring;
- fly-by-wire/fly-by-light;
- secondary load paths;
- duplex hydraulic systems;
- spring return system;
- back-up control system;
- automatic flight control systems with adjustable control authority;
- engine chop switch/throttles;
- twin TRs;
- novel ducted fan systems;
- variable camber fin;
- controllable main rotor speed;
- duplex/robust simplex TR drives.

A number of the above technologies are for post-failure use, for example the drag chute and back-up control system. However, technologies like fly-by-wire or fly-by-light can be used to reduce the control system failure rates and to build in redundancy and self-repair functions [19]. The major pre-failure mitigating technology requirement to reduce the impact of a complete TRF is that the fuselage with tail fin should be sufficiently directionally stable without the TR in operation in forward flight conditions, including climbs and descents. This can, however, have a detrimental effect upon the helicopter's operational characteristics; for example, large fins increase TR blockage and reduce sideways flight capability. The fuselage/fin design is therefore a compromise, dependant upon the design and mission requirements of the helicopter. Some studies have shown that to achieve sufficient yaw stiffness and damping in the absence of a TR, very large fin areas may be required which can cause problems of weight and structural strength [19,20,21].

It is appreciated that there are other operational systems not considered here such as the active rudder on the T-tail of the MD Helicopters NOTAR types.

2 Description of the prevention and mitigation technologies

2.1 **Drag chute**: The drag chute operates by generating a force in the opposite direction to the motion of the body to which it is attached. It has many advantages - it is relatively light weight, can be retrofitted to aircraft and can be used in situations of TRDF and TRCF. The drag chute's restoring moment increases with increasing sideslip and will also correct nose down pitching tendencies in the event of gearbox or TR hub component loss. The ability to constrain pitch attitude can be important because, following loss of TR thrust, the collective has to be lowered to reduce the dynamic yaw. Lowering the collective lever on a number of helicopter designs restricts the amount of cyclic range available to the pilot for pitch control. The ability of the drag chute to constrain yaw is dependent on the severity of the failure, pilot intervention time and drag chute deployment time and it is unlikely that the transient yaw rate would be reduced. However, assuming the aircraft structure survived the transient motion, the deployed chute would reduce further yaw motion and assist the pilot in regaining control. If correctly sized for the aircraft type, it could also enable a stable power/speed combination to be achieved in forward flight. The drag chute would be located in the back and bottom of the tail cone, suitably protected from environmental elements. Deployment of the chute on a small length tether or telescopic pole and short tether would be accomplished by a small pyrotechnic charge. The telescopic pole has the advantage of increasing the chute's moment arm and keeping it away from the main rotor (MR) and TR discs. A previous Bell patent exists for a similar system but considers the application only to control yaw. The possible disadvantage of the drag chute is that, because it produces additional drag when deployed, it could have an impact on the range capabilities of the helicopter. The impact of accidental deployment would also have to be considered. The drag chute could provide some limited benefit in reducing yaw rates following TRFs in low speed and hovering flight.

2.2 **Inflatable fin**: The inflatable fin has similar benefits to the drag chute, although in hover it will be less effective as it is designed to produce lift and additional yaw stiffness in forward flight to compensate for loss of the TR. The inflatable fin could be located on the bottom of the tail boom as far back as possible, or as an extension to the leading or trailing edges. In the lower position, it should be more effective in the descent than the conventional tail fin, since it would be subject to relatively undisturbed airflow. Its protection from the environment and deployment would be similar to that of flotation equipment fitted to offshore operating helicopters. The disadvantages are that it is difficult to retrofit and there is a weight and moment penalty associated with the compressed gas bottle required to inflate the fin. The issues of pilot intervention and drag chute deployment times and accidental deployment of a drag chute are also applicable to an inflatable fin.

2.3 **Spring Bias Unit/Negative Force Gradient Spring**: The Spring Bias Unit (SBU) and Negative Force Gradient (NFG) Spring are used in a number of aircraft designs, which operate with simplex hydraulic systems requiring a manual reversion capability. Their primary aim is to reduce the loads at the pedals during hydraulic power-off conditions. However, their inclusion in the control system does enable the TR control loads to be tuned to give a zero load condition at a TR pitch suitable for continued flight at minimum power and for low speed run-on landings. Therefore, in the event of a control rod failure to the TR, switching off the hydraulics to the TR servo enables a fail-safe TR pitch to be achieved.

2.4 **Fly-by-wire/fly-by-light**: Fly-by-wire/fly-by-light (FBW/FBL) systems enable a more damage tolerant control system to be designed and, if sufficient redundancy is built into the system, can reduce signalling failures. In the fixed wing world, FBW systems coupled to computers and aircraft sensors and actuators enable the effects of damaged control systems to be mitigated [22]. The fixed wing approach has not yet reached the same level of maturity in the helicopter world; there is no operational FBW/FBL rotorcraft. However, the benefits of being able to remove large numbers of mechanical control components with the possibility of building the control paths into the structure (e.g. optical fibres for FBL), will inevitably be capitalised upon by future helicopter designers.

2.5 **Secondary load paths**: The TR control circuit on the Sikorsky Black Hawk includes secondary load paths in its control rods and bell-crank pivot points. If a control circuit failure occurs at a bell-crank or a control rod end, a secondary pivot point takes over, although this does result in lost motion in the control circuit. General control can be maintained albeit with increased pilot workload. The Black Hawk also includes a secondary load path in the TR cable quadrant; in the event that a single cable failure occurs, a spring provides the lost cable loads, enabling the remaining cable to provide full control. Figure 5-1 shows the redundant cable quadrant mechanism.

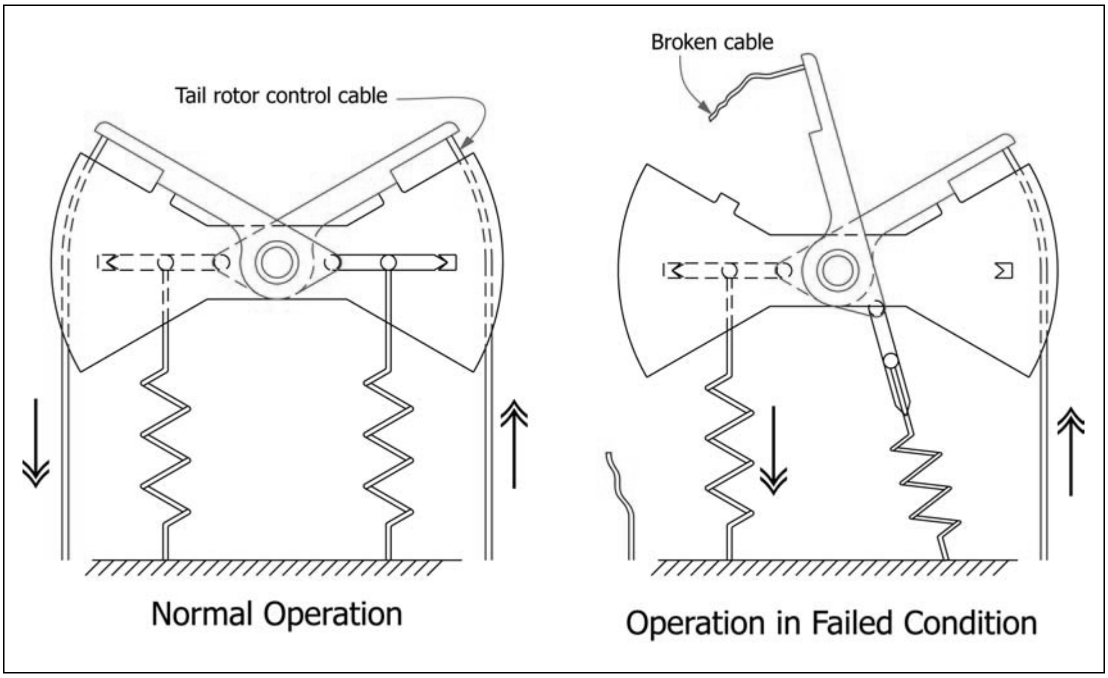

Figure 5-1 TR redundant cable

2.6 **Duplex hydraulic systems**: Duplex hydraulic systems have reduced the need to cater for manual reversion (SBU/NFG) in the event of hydraulic failures. However, duplex hydraulic systems do not remove the need to tune the TR to ensure that mechanical failures between the hydraulic servo and the TR, or total loss of hydraulic power result in the TR pitch migrating to a fail-safe value.

2.7 **Spring return system**: In the event of a control rod failure between the pilot and hydraulic servo (even if a duplex hydraulic system is fitted), the hydraulic servo should be driven to a position that equates to a fail-safe pitch. A fail-safe pitch enables continued flight at minimum power and enables a run-on landing to be performed. This can be achieved using a spring return system attached to the servo jack's input. In the event of a control rod failure between the pedals and hydraulic servo jack, it will be returned to a fail-safe pitch position by moving the input to a predefined position.

2.8 **Back-up control system**: The AH-64 Apache features a Back-Up Control System (BUCS) in all axes, which enables the pilot to use 100% authority FBW signalling of the servo jacks in the event of control rod failures, caused either through severing or jams. In the event of a control circuit jam a shear pin has to be broken to enable control to be maintained. It should be noted that all automatic stability augmentation is lost when the BUCS is activated.

2.9 **Automatic flight control systems with adjustable control authority**: In current helicopters, the Automatic Flight Control System (AFCS) is usually allowed about 10% control authority. Under this proposal, in the event of a control run failure, the pilot switches the AFCS authority to 100% (as happens automatically in the Apache BUCS). This solution requires that the AFCS series actuators be built into the hydraulic jack rather than being placed in the mechanical control run. The system described would enable the pilot to retain control of the helicopter via the AFCS computer. For example, in the event of a TR control run failure and the pilot selecting full AFCS authority, a possible mode of operation would have the primary input to the AFCS computer as data from a slip vane which would adjust the series actuators to maintain zero sideslip. Careful consideration would have to be given to the failure modes and effects analysis for the system.

2.10 **Engine chop switch/throttles**: For maximum effectiveness this system is located on the collective and allows the engines to be cut off without the need for the pilot to remove his hands from the controls. The alternative to the chop switch is to locate the engine throttle controls on the collective, again this enables the engines to be cut or set to any torque value without the need to remove the hands from the controls. In the event of a TRDF, the ability to enter autorotation quickly is important in order to contain the dynamic yaw imposed by the loss of TR thrust. Of equal importance is the ability to cut the engines without the need for the pilot to remove his hands from the controls, particularly on aircraft with low fuselage yaw stiffness and where MR speed control in autorotation requires constant adjustment of the collective. The effect of re-engaging the engines and generating a torque on the fuselage could have disastrous consequences.

2.11 **Twin TRs**: Twin TR (TTR) solutions have been suggested in the past as a means of mitigating against the effects of TR loss [21]. In the event of one TR getting damaged the other provides sufficient control to allow the helicopter to be landed. TTRs also offer the benefit of reduced fin blockage in low speed flight by using a V-tail arrangement. Unfortunately, as the major accidents associated with TR appear to be TRDFs, a single drive system feeding both TRs would offer little additional benefits. Equally, damage caused to one TR by FOD could also cause damage to the other TR. Ideally a duplex drive system is required but, unfortunately, this generates additional weight and complexity.

2.12 **Novel ducted fan systems**: A duplex drive system increases weight and complexity unless a novel design solution can be found like the ducted fan which provides both propulsion and yaw control. The TR faces aft with its centre located in line with the tail drive, yaw control being achieved by variable direction guide vanes in the TR wash. The benefits of this arrangement are that the TR or twin TRs can be placed on the end of the drive shafts without the need for intermediate or tail gearboxes.

More conventional ducted fans have been in operation for some time, for example, the Fenestron and NOTAR systems. The latter does have benefits in forward flight because the anti-torque moment required to balance the MR torque is supplied by an aerodynamic surface. However, they also have disadvantages, such as reduced autorotative handling characteristics. The Fenestron solution to yaw control, on the other hand, has resulted in a number of accidents involving one particular type in low speed flight through what is believed to be loss of Fenestron effectiveness.

2.13 **Variable camber fin**: In order to reduce TR thrust in forward flight and therefore reduce the possible dynamic effects induced by a TRDF, increased fin off-loading could be generated by increasing the camber of the tail fin. The advantage of this technique over increasing the fin area is that, in the hover, fin blockage is not increased. The camber increases could be achieved by incorporating nose slats and trailing edge flaps, the adjustment of which would be set by actuators as in fixed wing aircraft designs. Coupled to a flight computer, the fin lift would be adjusted to off-load the TR in forward flight. An advantage of the variable camber fin over either the drag chute or inflatable fin is the near zero deployment time and benign inadvertent deployment characteristics. The disadvantages of this system are its complexity and the increased weight at the tail (although use of modern electric actuation systems would reduce this penalty). Additional weight at the tail moves the helicopter’s centre of gravity aft, which impacts upon the MR longitudinal cyclic pitch requirements. Alternative methods may be available to achieve the same effect as slats and flaps, such as surface blowing, where the majority of the added weight could be situated forward of the fin.

2.14 **Controllable MR speed**: It was found during validation of the Lynx aircrew TRF advice [5] that the use of MR speed (N_R) control was a powerful tool in enabling the pilot to maintain control of the helicopter in low speed and hover conditions following a TRCF. If the TRCF resulted in a high thrust condition from the TR, by reducing N_R the TR thrust is reduced and, if power is maintained, the MR torque is increased. If a TRCF results in a low TR thrust condition, increasing N_R increases TR thrust and, if power is maintained, reduces MR torque. This technique has been shown to work during TRCF incidents [14].

2.15 **Duplex/robust simplex TR drives**: The TTR solution proposed in 5.2.11 would ideally be associated with a duplex TR drive system for complete redundancy. This solution could also be considered for the conventional single TR configuration, and could be composed of duplex systems up to the ITRGB or even the TRGB. However, the fact that TRDS failures caused through external TR impact might affect both drive systems should be considered. The ability to withstand such shock loadings could be achieved using lightweight robust drive systems equipped with, for example, torque-limiting devices. The benefit would be that TR drive would only be lost temporarily, assuming that the TR itself remained effective. Quantification of the design, weight and complexity issues associated with duplex and robust simplex drives appears not to have been previously carried out, and provision of such complex design solutions is outside the scope of this study. It is recommended that feasibility studies be carried out to address these issues.

3 Utility of the prevention and mitigation technologies

Analysis of the occurrence data given in [10] and summarised in Section 2 revealed that the four major causes of TR-related occurrences are:

a) the TR striking an object (30%);

b) TR drive system failures (30%);

c) the TR being struck by an object (15%);

d) TR control system failures (8%).

A tail proximity warning device would help remove the first major cause of TR-related occurrences. The most significant benefits from the technologies discussed above therefore would be to tackle the TR drive system failure cases. The consequences of a TRDF can be addressed during the initial design process, particularly in forward flight by reducing the TR thrust requirements, and for all flight regimes by considering redundancy in the anti-torque system as a whole. It should be understood, however, that stable basic fuselage characteristics in forward flight, however, do not necessarily assist in the hover and, under certain operational environments, can impose penalties because of their effects upon low speed performance [21]. Incorporation of retrofit stabilising devices could hold many benefits and address the TRDF concerns for both new and existing designs.

There are certain features, however, which should be incorporated in all future designs involving the classic TR system. In particular, a fail-safe pitch condition should be built into the TR during the design process to ensure that the TR returns to a suitable pitch in the event of a mechanical failure between the TR and control jack, or between the pilot’s pedals and the jack. Additionally, the tail fin drive shaft covers should be hinged away from the TR such that in the event of becoming unfastened in flight they will not contact the TR. Particular attention should also be paid to the fastening system design. This is of particular importance because the loss of a TR drive shaft cover, which forms the leading edge of the fin, will also result in a substantial reduction in fuselage yaw stiffness, and therefore the ability of the pilot to retain heading control, even when the helicopter is in a power-off descent. Similar importance should be placed on fastenings associated with removable covers.

4 Comparison between TR, fin and drag chute

The following analysis has been undertaken to investigate the individual merits of generating a restoring moment from a TR, fixed surface and from a parachute.

4.1 **TR**: The fully operational TR provides three main functions:

a) **Torque reaction**: this counters the effect of the yawing moment associated with the MR.

b) **Directional stability**: the loaded TR inherently provides yaw stiffness and damping, providing directional stabilising moments following sideslip excursions.

c) **Yaw control**: by varying the collective pitch of the TR to alter the amount of torque reaction, the heading of the aircraft can be adjusted to generate a yaw rate or sideslip as required.

The loss of TR drive therefore has a major influence over the pilot’s ability to maintain overall control of the helicopter. Assuming the pilot can remove the MR torque quickly to reduce the dynamic effect in yaw, he then has to overcome the loss of heading control and the loss of fuselage yaw stiffness. Many fuselage designs lack basic yaw stiffness once the TR has stopped. The yaw stiffness term (in lb ft/deg) associated with the TR in forward flight can be approximated by:

$$\left(\frac{dN}{d\beta}\right)_{TR} = \frac{0.5\rho_0\sigma(\Omega R)^2\pi R^2 4\mu^2 a_0 0.0174S}{(8\mu + a_0 S)}$$ **Equation 5-1**

Where:

- N is the yaw moment;
- β is the sideslip angle;
- ρ_0 is the air density at sea level ISA;
- σ is the density ratio;
- Ω is the rotor speed;
- R is the rotor radius;
- μ is the advance ratio;
- a_0 is the rotor lift curve slope;
- S is the rotor disc area.

In the event of a TRDF the basic TR yaw stiffness term has to be replaced, especially if the fuselage yaw stiffness is low. In addition, for continued powered flight, the anti-torque thrust has to be replaced. The ability to continue powered flight will depend on the vehicle's inherent stability and the type of TRF. There are types where there is no acceptable power/speed combination, and an immediate autorotative landing is the only possibility. Types that are able to continue with powered flight after loss of TR thrust include both helicopters with conventional TRs, and examples with ducted or shrouded fan TRs where significant anti-torque thrust in forward flight is generated from the fixed fin. However, although the large fin has a benefit in forward flight, it can cause severe handling problems in low speed flight if strong crosswinds are present, and would actually exacerbate the situation in the event of a HP TRCF. The use of an emergency device like a drag chute, inflatable fin or a means of generating additional fin lift are therefore good ways of replacing the lost yaw stiffness.

4.2 **Vertical fin**: The yaw stiffness term (in lb ft/deg) of a vertical fin in comparison to that generated by the TR is given by:

$$\left(\frac{dN}{d\beta}\right)_{fin} = 0.5\rho_0\sigma V^2 l_t S_F a_{Fin}$$ **Equation 5-2**

Where:

- V is the forward velocity;
- l_t is the longitudinal separation between the MR and TR hub centres (in this case approximately 25 ft);
- S_F is the fin area;
- a_{Fin} is the fin lift curve slope.

The $(dN/d\beta)_{TR}$ and $(dN/d\beta)_{\text{Fin}}$ for a Lynx-sized helicopter can be seen in Figure 5-2, this indicates that, for a fin area of 11.5 ft^2, the $(dN/d\beta)_{\text{Fin}}$ at 100 knots is equivalent to 33 % of $(dN/d\beta)_{\text{TR}}$ Therefore, in order to replace the yaw stiffness term alone, the fin would have to be three times as large. To enable the fin to generate an anti-torque thrust as well as supply suitable $dN/d\beta$ would require camber, increased incidence or both.

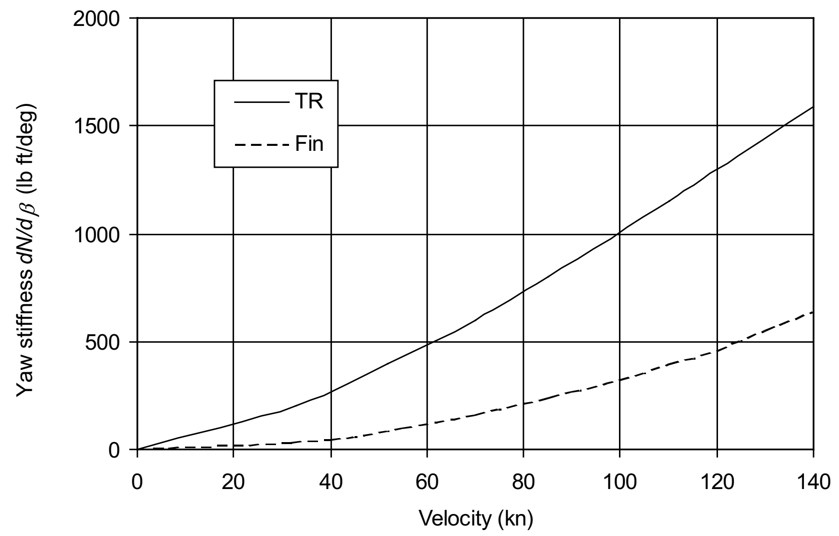

Figure 5-2 $dN/d\beta$ for a Lynx-sized aircraft

The lift L (in lb) generated by the fin in forward flight is given by:

Equation 5-3

$$L = 0.5\rho_0 \sigma V^2 S_F a_{Fin} \beta$$

The graph in Figure 5-3 demonstrates that at 100 knots, the 11.5 ft^2 fin would have to produce approximately 450 lb of lift to replace the anti-torque thrust generated by the TR. This would equate to increasing the fin incidence from 4° (as shown) to approximately 35°, assuming the fin did not stall, or the fin area would have to be in the order of 90 ft^2. These calculations are based on a very low lift curve slope associated with low aspect ratio lifting surfaces, i.e. similar to the current Lynx tail fin. Improved fin design could reduce these numbers, however, they do serve to illustrate that a significant increase in area is required to replace the TR thrust and damping in forward flight.

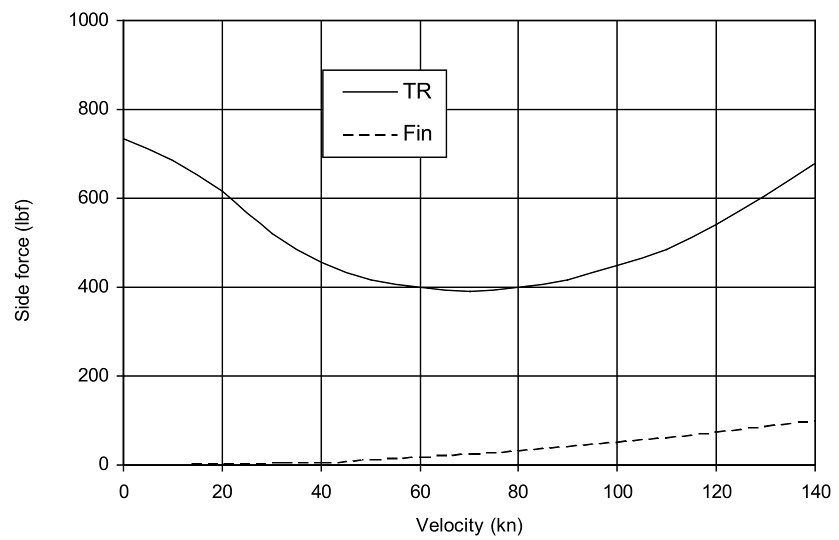

Figure 5-3 Fin lift and net TR thrust requirement for Lynx-sized aircraft

Drag chute: The drag D_{chute} (in lb) generated by a parachute can be treated in this initial study as the drag generated by a solid disk (drag coefficient $C_{d0}=1$) of a given frontal area S_P:

$$D_{chute} = C_{do} 0.5 \rho_0 \sigma V^2 S_P$$ **Equation 5-4**

The restoring yaw moment term (in lb ft) generated by the drag chute is therefore given by incorporating the tail arm over which it acts and the sideslip angle, as shown in Equation 5-5 and in Figure 5-4.

$$N = l_t C_{do} 0.5 \rho_0 \sigma V^2 S_P \sin \beta$$ **Equation 5-5**

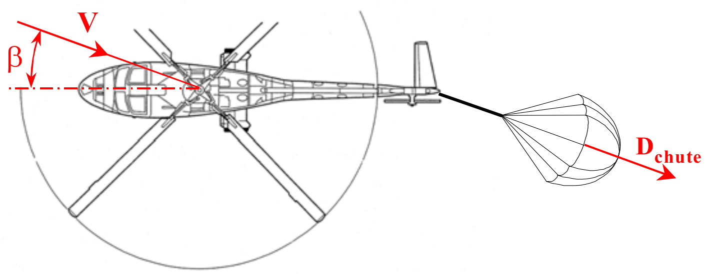

Figure 5-4 Drag parachute operation

The drag chute's restoring moment term is therefore a function of speed and sideslip. Figure 5-5 shows the effect of a parachute with a 5 ft^2 frontal area acting on a Lynx-sized helicopter, and clearly indicates that, as the sideslip angle increases, so does the restoring moment. The sizing of the chute for each aircraft type would be on the basis that continued flight would be at a minimum power speed and minimum power condition. To attempt to replace the complete TR thrust and generate the necessary anti-torque moment at 100 kn and 10° sideslip using a parachute, without a change in power or speed condition, would require a parachute frontal area in the order of 75 ft^2 which would be impractical.

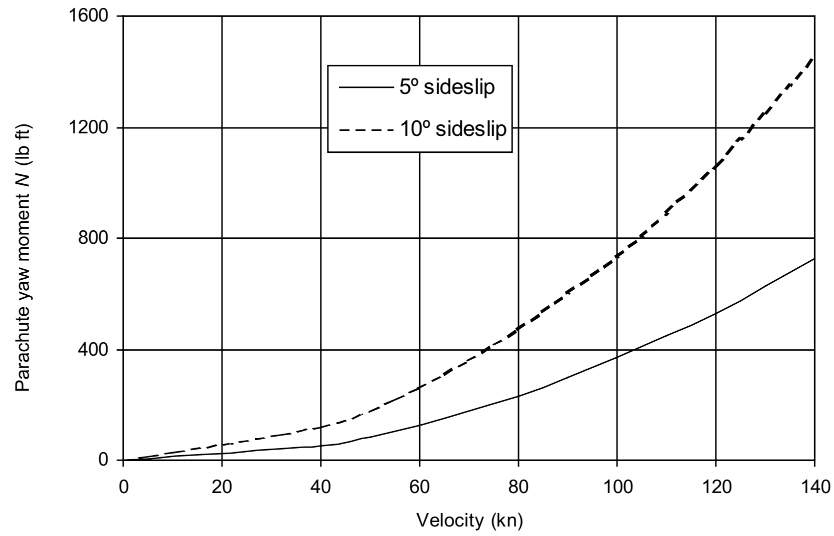

Figure 5-5 Parachute restoring moment for a Lynx-sized aircraft

These calculations have been considered in isolation to illustrate the differences between the TR, fin and parachute; however, the situation is far more complex particularly since fuselage yawing moment characteristics with sideslip can also influence the requirements from both fin and parachute. The analysis does, however, serve to illustrate the relative sizes of fin and parachute required to enable the helicopter to continue uninterrupted flight at the same MR power condition following loss of TR thrust. The parachute does have one other feature in that it generates drag, and therefore under trimmed flight conditions will reduce helicopter speed for a given MR power condition. This can be a benefit during control jam situations that result in fixed TR pitch conditions associated with low levels of MR power. Continued flight at minimum power can be achieved but, as the speed is reduced to attempt a run on landing, heading control becomes more difficult as the MR torque rises and the helicopter nose starts to drift away from the flight direction. Further applications of collective to cushion a landing drive the nose further away from the flight path. The deployment of the drag chute also helps to constrain heading. Reduction of the transient yaw is highly dependent upon the pilot intervention and drag chute deployment times, however, and the effects of inadvertent deployment could be hazardous. The increased drag of the parachute may also result in increased MR head/ mast bending, depending on forward speed. This could well have a dramatic affect on MR fatigue life and it would be essential to ensure that the head would survive the remainder of the flight, especially for a head approaching the end of its normal fatigue life. The crew would have to take account of a reduction in range (e.g. by 6% for a typical Lynx over water mission) once the chute was deployed, although this would of course be secondary to the need to recover from a TRF.

5 Analysis of the benefits of prevention and mitigation technologies

An analysis of the previously described technologies was applied to 29 of the 31 occurrences detailed in [10] and appendix A (i.e. omitting those caused by failure of the tail pylon structure). The detailed descriptions represent a good cross-section of TR associated occurrences, although their inclusion was based solely on the availability of adequate information. The lightweight robust TR drive shaft and in-line ducted fan technologies were considered as separate simplex systems, whereas the twin TR/fan and duplex conventional TR drive shaft technologies were considered together as a combined system. This analysis indicates that 90% of cases could have benefited from the incorporation of one or more of the technologies. For those cases **resulting** in TRDF the figure would be 100%. For those cases **caused** by failure of the TR drive system, and through TR/object impact, the figures would be 88% and 100% respectively. Considering the proportion of TR occurrences associated with TR drive system failures, (30% overall of which shaft and gearbox failures contributed to 13%), a duplex drive system could hold many advantages but would require a detailed and thorough investigation of the design issues. The more immediately available technologies (retrofit devices), however, could have reduced the severity in 79% of all cases. For those cases **resulting** in TRDF the figure would be 84%. For those cases **caused** by failure of the TR drive system, and through TR/object impact, the figures would be 69% and 100% respectively. The sample analysed represents only 20% of the 144 UK occurrences detailed in [10]. However, extrapolation of the analysis to cover all those occurrences indicates that at least 66 of the 78 such cases resulting in TRDF, and 114 overall, could have benefited from the technologies.

The technologies providing benefit in most cases were the drag parachute, inflatable fin and twin TR/fan with duplex TR drive. The in-line ducted fan and variable camber fin solutions also featured to a lesser extent and, for the TRCF cases, the SBU-type devices were largely beneficial. Most of the other technologies were not judged to be beneficial in the limited cases studied, although new technologies (e.g. fly-by-wire) have the potential to reduce the instances of signalling failure, both through enhanced inherent reliability and increased opportunity for redundancy. However, failures between the hydraulic servo and the rotating controls still require a fail-safe pitch condition to be incorporated at the outset of the design.

The tail proximity warning device discussed in [10] and Section 4 would help remove one of the major causes of occurrences – the tail hitting an object. The most significant benefits from the mitigating technologies discussed in this report would be to tackle the TRDF cases. This can be addressed during the initial stage in the design process by reducing the TR thrust requirements in forward flight or, at a later stage, by incorporating a retrofit stabilising device. Stable basic fuselage characteristics in forward flight, however, do not necessarily assist in hover and under certain operational environments can impose penalties because of their effects upon low speed performance [21]. Therefore, a retrofit or additional design feature which can be used in the event of an emergency can hold many benefits. The occurrence analysis also shows that the design of a lightweight robust TR drive system could significantly reduce the TRDF rates, especially if it could cope with TR impact shock loadings. Additionally, robust panel latching and fastening systems are of equal importance to that of providing retrofit stabilising devices.

The consequences of transient effects on deployment and failure of the mitigating technologies must be considered alongside the potential for assisting in the recovery from TRFs. Inadvertent deployment is an issue for all deployable and reversionary devices (both manual and automatic), since this would result in changes to yaw stiffness and damping which could, ironically, be mistakenly diagnosed as TRF.

Improper deployment of the drag chute would be hazardous, particularly if it resulted in contact with the rotating TR during TRCF, possibly resulting in TRDF and/or damage to the empennage.

6 Conclusions

Cross-references to the main text are given in parentheses.

- TRCF problems can be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch (e.g. as currently used in some types of Spring Bias Unit (SBU)). The fail-safe pitch should function in the event of a control rod disconnection between the pedals and the servo or between the servo and the TR (3).
- Increasing fin effectiveness off-loads the TR and therefore the severity of a TRF during forward flight. This can be achieved through increasing fin size or through physical or effective changes to fin camber. Increasing fixed fin size could dramatically reduce the sideways flight capability, however, and could also be a disadvantage in HP TRCFs, where the increased side force would exacerbate the problem. Containment of the transient yaw during a severe TRF would require considerable extra fin effectiveness (4.1).
- To attempt to replace the **complete** TR thrust and generate the necessary anti-torque moment at 100 kn and 10° sideslip with a parachute, without a change in power or speed condition would require a parachute frontal area in the order of 75 ft^2 which would be impractical. However, the drag chute has the ability to be retrofitted, and it requires a relatively small area to produce **significant** yaw stiffness and does not affect low speed performance. It can also be used to control pitch attitude in the event of loss of mass from the tail. The drag chute can also be used in the event of TRCFs that result in both high and low TR thrust conditions. Since the parachute generates drag, under trimmed flight conditions it will reduce helicopter speed for a given MR power condition. This can be a benefit during control jam situations that result in fixed TR pitch conditions associated with low levels of MR power. The deployment of the drag chute also helps to constrain heading. Reduction of the transient yaw is highly dependent upon the pilot intervention and drag chute deployment times, however, and the effects of inadvertent deployment could be hazardous. The increased drag of the parachute may also result in increased MR head/mast bending, depending on forward speed. This could well have a dramatic affect on MR fatigue life and it would be essential to ensure that the head would survive the remainder of the flight, especially for a head approaching the end of its normal fatigue life. The crew would have to take account of a reduction in range (e.g. by 6% for a typical Lynx over water mission) once the chute was deployed, although this would of course be secondary to the need to recover from a TRF (4.3).
- A twin TR system could offer many benefits; however, it should to be associated with a twin drive shaft system and duplex controls for the maximum benefit to be gained, although this will inevitably generate additional weight and complexity. Quantification of the design, weight and complexity issues associated with duplex and robust simplex drive systems appears not to have been previously carried out and provision of such complex design solutions is outside the scope of this study (2.15).
- The consequences of transient effects on deployment and failure of the mitigating technologies must be considered alongside the potential for assisting in the recovery from TRFs. Inadvertent deployment is an issue for all deployable and

reversionary devices (both manual and automatic), since this would result in changes to yaw stiffness and damping which could, ironically, be mistakenly diagnosed as TRF. Improper deployment of the drag chute would be hazardous, particularly if it resulted in contact with the rotating TR during TRCF, possibly resulting in TRDF and/or damage to the empennage (5).

- Appendix A contains a more detailed analysis of the potential benefits of the prevention and mitigation technologies, assessed against a number of occurrences for which sufficient understanding of the circumstances is available to make such judgements. From this analysis, it is considered that the various technologies would have produced a beneficial effect in 90% of all the cases. For those cases **resulting** in TRDF the figure would be 100%. For those cases **caused** by failure of the TR drive system, and through TR/object impact, the figures would be 88% and 100% respectively. If the retrofit devices alone are considered (i.e. excluding twin TR/fan with duplex TR drive) the technologies would still have produced a beneficial effect in 79% of all the cases. For those cases **resulting** in TRDF the figure would be 84%. For those cases **caused** by failure of the TR drive system, and through TR/object impact, the figures would be 69% and 100% respectively. The technologies providing benefit in most cases were the drag parachute, inflatable fin and twin TR/fan with duplex TR drive. The in-line ducted fan and variable camber fin solutions also featured to a lesser extent and, for the TRCF cases, the SBU-type devices were largely beneficial. Most of the other technologies were not judged to be beneficial in the limited cases studied. The sample analysed represents only 20% of the 144 UK occurrences detailed in [10]. However, extrapolation of the analysis to cover all these occurrences indicates that at least 66 of the 78 such cases resulting in TRDF, and 114 overall, could have benefited from the mitigating technologies (5).

7 Recommendations

Cross-references to the main text are given in parentheses.

- <u>TR control failure (TRCF) problems should be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch.</u>
- It is recommended that studies be conducted to examine how best to achieve increased fin effectiveness without unduly compromising vehicle performance (4.1).
- It is recommended that feasibility studies be carried out to quantify the design, weight and complexity issues associated with duplex and robust simplex drive systems (2.15).

Section 6 Advanced Flight Simulator trials

1 Introduction

The work reported on in this section, together with the work reported on in Sections 4 and 5, covers objectives 3 and 4 as defined in Section 1. Overall trial methodology and data recording are described in 2 and 3 respectively. The individual trials are then described in 4 and 5 respectively, with summary conclusions and recommendations provided in 6.

2 Methodology

2.1 General

2.1.1 **AFS configuration**: All tasks were carried out using a land-based scenario and visual database, simulating full daylight and unlimited visibility conditions. At the outset of the project a preference for use of Sea King and/or Puma simulation model types was expressed; however, the TRF projects which were expected to provide them had not progressed as planned, so the baseline aircraft configuration used for generating these data was the QinetiQ Helisim Lynx model [8]. Helisim [9] is a flight mechanics model developed by QinetiQ Bedford for use in real time simulation on the AFS, and has been used extensively within QinetiQ, in particular it was used in the Lynx configuration for the Lynx TRF programme [5]. A disk model with quasi-steady inflow and flapping dynamics represents the main rotor. The model uses an equivalent centre spring to represent blade flapping stiffness and assumes rigid blades. The TR is modelled by a simple actuator disk with no flapping dynamics. The study was not intended to be Lynx-specific, but to explore the potential for generic improvements in survivability of TRFs through improved understanding of airworthiness requirements and mitigating technologies. Although not generic, changes to appropriate parameters were performed on this model to achieve each trial's aims. For example, the equivalent MR hinge offset was reduced in some cases to explore the impact of an articulated MR system as found on aircraft like the Sikorsky S-76. The rotary wing cockpit is essentially a generic representation, but it is dimensionally based on the Lynx with appropriate inceptor positions.

2.1.2 **Test matrix**: The test plans were derived from a prioritised list of possible candidate test scenarios associated with four TRF types and the three TRF phases (described in Sections 1 and 2 respectively) as shown in Table 6-1.

Table 6-1 Test matrix

Phase	Type			
	TRDF	TRCF		
		HP	LP	TP
Transient	1	1	2	3
Manoeuvre	3	1	2	3
Landing	2	2	2	2

The nominal values of TR pitch used for HP and LP TRCFs were 26° (0% pitch, full left pedal) and –4° (88%) respectively. The TR pitch angle set for the TP TRCF cases was 5.3° (61%) to reflect the approximate value that would result from operation of the Lynx SBU. The HP case therefore represents a runaway to, or freeze at, maximum pitch, and the TP and LP cases represent different pitch freeze conditions. Each case needed to be considered at different speeds; the three initial speed conditions simulated are shown in Table 6-2.

Table 6-2 Initial speed conditions

Speed condition	Speed (kn)
Hover	0
Mid speed	80
High speed	140

During the trials, each of the pilots was initially given the opportunity to explore the general handling characteristics of the simulated aircraft and to familiarise himself with the simulation environment. For expediency, the test points for the failure transient and manoeuvre flight phases were combined so that the end of the transient condition became the start of the manoeuvre flight assessment. The landing phase test points were simulated separately in order to establish reasonably consistent and stable initial conditions.

2.2 Failure transient and manoeuvring flight phases

Use of the ADS-33D yaw coupling and turn co-ordination requirements for power-on manoeuvring were discussed in Section 3. However, in the context of the trials, whilst it was the Level 2/3 and Level 3/4 boundaries that were of most interest, considerably more extensive testing than was permitted in this programme would have been required to define these. Handling in all phases was investigated from the standpoint of pilot subjective opinion only.

2.2.1 **Pilot intervention time**: From the initial conditions a fault was seeded and, for the purposes of the simulation, the pilot was alerted to the failure by an audio tone This tone was activated at a set time after failure injection, referred to as the pilot intervention time (PIT). The modelling of the PIT, regarded as the time taken from diagnosis to initial pilot response had been demonstrated from the Lynx trial [5] to be critical to the fidelity of the simulation. If a long time delay is imposed on the pilot, in some cases the situation will be beyond recovery before any action is taken. Alternatively, too short a response time can be unrealistic and will falsely influence the outcome of the test point. A one second delay was considered too short and 4 seconds was too long for a successful recovery. A value of 2 seconds was therefore used as a compromise in order to provide some realism and to give the pilot a chance of recovering the aircraft. In a separate research programme [23], PITs were assessed in various training simulators for different emergencies. The conclusion for the TRF cases was that a detection time of between 1 and 3 seconds was realistic to identify that the failure had occurred, and that a particular response was required.

2.2.2 **Run down time for TRDF**: Following a TRDF there will usually be a finite period of time before the effectiveness of the system is lost. For a TRDF where the power source is disconnected from the TR, the disc will stop turning and lose thrust after a few seconds. Once again, in previous trials this run-down time was examined (1 second to 40 seconds) and, after advice from the RAFHS and Westland Helicopters Limited (WHL, part of AgustaWestland), a time of 1 second was agreed upon. It was considered that this represented what is generally considered to be a very rapid and catastrophic failure.

2.2.3 **Onset time for TRCF**: For the TRCF cases it is more likely that there will be a gradual degradation of the TR function over a few seconds or possibly over several minutes. The nature of the failure will determine the time constant applicable. From narrative reports of TRCF occurrences there is generally a period of time over which the pilot is aware of an increasing need for an abnormal yaw pedal input to maintain the desired flight path. In these trials, an onset time of 4 seconds was adopted as a representative period over which the problem develops. Too short a time and the PIT becomes an issue, too long a time and transient reactions and responses are minimal.

Each test point was first assessed to determine whether a trim condition could be achieved following the failure. If trim could be achieved then controlled flight manoeuvres to the left and right were assessed; the pilots were required to alter heading by 45°. This represents a fairly gross heading change, and certainly significant enough to be used to manoeuvre the aircraft towards a landing area. Greater turn steps could be achieved through multiple applications, whereas smaller yaw excursions would not have been identifiable from stabilising manoeuvres. All tests were run from a nominal initial altitude of 3000 ft.

2.3 Landing Phase

In order to establish reasonably consistent and stable initial conditions it was necessary to initiate each of the test points in this phase from the pre-failure state, with the conditions chosen such that the initial transient condition could be controlled. Where the transient was not stabilised, the test point was aborted.

The final touch down is considered to be the most difficult to represent in ground-based simulation due to the visual cue deficiencies close-in and the complexity in modelling the reaction of the aircraft as it meets the ground. This is due in part to the physical conditions of the landing area including slope, surface cover and composition (grass, mud or tarmac) and the meteorological conditions. Therefore, without being able to assess the response post impact/landing, the test points were analysed off-line to determine survivability by noting the vehicle terminal conditions at touchdown i.e. drift angle (angle between aircraft centreline and direction of flight relative to the ground) and maximum vertical and forward velocities.

3 Data recording

3.1 Flight parameters

The modelled flight parameters were recorded at a sample rate of 25 Hz and are detailed in Table 6-3. Quantitative assessment was conducted by post-trial analysis of performance data and video recordings. Data logging was sometimes curtailed after stable conditions were reached at the end of the transient phase. The conventions used are shown in Table 6-4.

Table 6-3 Recorded flight simulation parameters

<table>
<tr><th colspan="2">Data recorded for each phase</th></tr>
<tr><th>Transient and Manoeuvre</th><th>Landing</th></tr>
<tr><td colspan="2">Displacements and attitudes
Velocities and accelerations
MR torque
Control positions
Rotor speeds
TR collective pitch</td></tr>
<tr><td>Altitude loss</td><td>Touchdown parameters:
vertical velocity
forward velocity
drift
roll and pitch angles
yaw rate</td></tr>
</table>

Table 6-4 Flight parameter conventions

Parameter	Convention
Collective control position	0% full down, 100% full up
Yaw pedal position	0% full left, 100% full right
Lateral cyclic position	0% full left, 100% full right
Longitudinal cyclic position	0% full forward, 100% full aft
Yaw rate	Positive nose right
Bank angle	Positive starboard down
Pitch angle	Positive nose up
Sideslip angle	Positive right (nose left)
Lateral velocity	Positive right
Height rate	Positive climb
Speed	Positive forward
TR pitch angle	Increasing with left pedal

3.2 In-cockpit questionnaire

In order to capture pilot subjective opinion, a detailed in-cockpit questionnaire (ICQ) was used which has evolved from experience in the design and conduct of flight experiments and simulation trials using the AFS. The ICQ combines the Cooper-Harper Handling Qualities Rating (HQR) scale ([11] and shown in Section 3), a failure/recovery rating (FRR) scale [24] and situation awareness ratings, and was intended to be applied in situ at the end of each test point. In practice the pilot referred to an ICQ proforma and relayed the various ratings and comments over the intercom for the trials team to record.

The ICQ (shown in Figure 6-1) appears complex but the procedure for recording the data was readily adopted by the trials team and, given the amount of information returned, economic to apply. The three components in order of appearance are:

a) Cooper-Harper HQRs;

b) FRRs;

c) situation awareness ratings.

The HQRs were awarded with respect to the handling qualities of the vehicle from the point the pilot took action i.e. after the PIT for the transient phase when, as will be seen, the failure transients were likely to have already taken effect. The FRRs were awarded with respect to recovery from the point of failure injection, and are arguably the most important ratings. Some of the HQR/FRR combinations may appear inconsistent, for example, adequate handling of the vehicle may have been possible in the air (post PIT transients) whilst the lateral velocity on landing may have resulted in rollover.

It was subsequently decided not to use the situation awareness ratings, partly due to the pilot being informed of the failure type beforehand, and partly due to the fact that similar issues would already have been assessed within the FRR.

3.2.1 **Cooper-Harper HQR procedure**: As a precursor to awarding an HQR, the ICQ included three scales labelled as follows:

a) Task performance

b) Task workload

c) System characteristics

These refer directly to the key rating factors that are an integral part of the Cooper-Harper decision tree and rating process shown in Section 3. In each case, the pilot should award a rating on a continuous scale from 1 to 5, where ‘adjectival’ descriptions are given at each integer point using descriptors based on appropriate wording taken from the decision tree. It is possible to derive ‘equivalent’ HQRs (EHQRs) based on the pilots’ individual ratings for task performance, workload and system characteristics that may be used as a consistency checking procedure. This approach is intended to provide a common understanding of the rating procedure between pilots and engineers, and ultimately gives rise to consistent sets of HQRs for test serials. The EHQR is not intended to be a replacement for the HQR but to highlight when anomalies occur.

Part 1 Cooper-Harper rating procedure

TASK PERFORMANCE	Clearly within desired performance limits	Desired performance marginally achievable	Clearly within adequate performance limits	Adequate performance marginally achievable	Adequate performance not achievable
Rating	1	2	3	4	5

TASK WORKLOAD	Low	Moderate	Considerable	Extensive	Intolerable
Rating	1	2	3	4	5

SYSTEM CHARACTERISTICS	Satisfactory	Minor but with annoying deficiencies	Moderately objectionable deficiencies	Very objectionable but tolerable deficiencies	Major deficiencies but controllable
Rating	1	2	3	4	5

HQR		1 to 3	4	5	6	7 to 9
Detrimental Factors		Neutral	Minor	Moderate	Considerable	Major
Rating		1	2	3	4	5
Vehicle Limits	Control margins					
	Power/Torque					
	'G'					
	Airspeed					
	Sideslip					
	Angular rates					
	Visual cues					
Simulation Cues	Instruments					
	Motion					
	Audio cues					
	Inceptors					

Part 2 Failure/recovery rating procedure

A B C D E F G H

Part 3 Situation awareness rating procedure

Level of awareness	Excellent	Good	Fair	Low	Poor
Rating	1	2	3	4	5
Onset of failure					
Corrective control action					
Proximity to limits					
Likelihood of collision					

Figure 6-1 In-cockpit questionnaire

For consistency checking, the awarded HQR should be within 1 point of the EHQR, where the EHQR is determined by application of the following rules:

- Take maximum rating from those awarded for task performance, task workload and system characteristics.
- Non-integer maximum ratings are to be rounded to the nearest integer.
- Derive the EHQR from Table 6-5:

Table 6-5 Equivalent HQR allocation

Maximum questionnaire rating	EHQR
1	1 to 3
2	4
3	5
4	6
5	7 to 10

The HQR is then awarded using the standard decision tree procedure as shown in Section 3. There is redundancy in this approach, but experience has shown that it does achieve the aim of ensuring consistency, which is particularly relevant if pilots of varying backgrounds and levels of experience are involved in the tests.

The rating scales immediately following the HQR are intended to identify key factors that have influenced the choice of rating and, in particular 'vehicle limits' and 'simulation cues' that may have had a detrimental effect on the evaluation. Again, ratings are awarded on a 1 to 5 scale, equating to a level of detrimental impact from 'neutral' to 'major'; neutral is taken to mean that the specified factor was of no concern, or was a positive attribute. Definitions of the rating factors are shown in Table 6-6.

Table 6-6 HQR influencing factors

Rating factor	Interpretation
Control margins	Proximity to control limits and perceived lack of control power.
Power/torque	Proximity to limits and perceived lack of adequate margins.
'G' forces Airspeed Sideslip Angular rates	Proximity to/likelihood of exceeding flight envelope limits.
Visual cues	Field of view and position, speed, height and height rate cues perceived from the outside visual scene.
Instruments	Display of primary flight and aircraft state information.
Motion	Missing motion cues (normal 'g', side forces etc.).
Audio cues	Rotor and airframe aerodynamic noise cues, alert signal tones.

3.2.2 **FRR procedure**: This section is for recording the rating that should be awarded using the standard decision tree procedure shown in Figure 6-2. It appears, with hindsight, that each of the pilots may have weighted their ratings differently, e.g. approach of limits versus the level of urgency used to make corrective inputs.

In the remainder of this report, the HQR and FRR may be referred to together; for example HQR 9 and FRR H as pilot rating 9H.

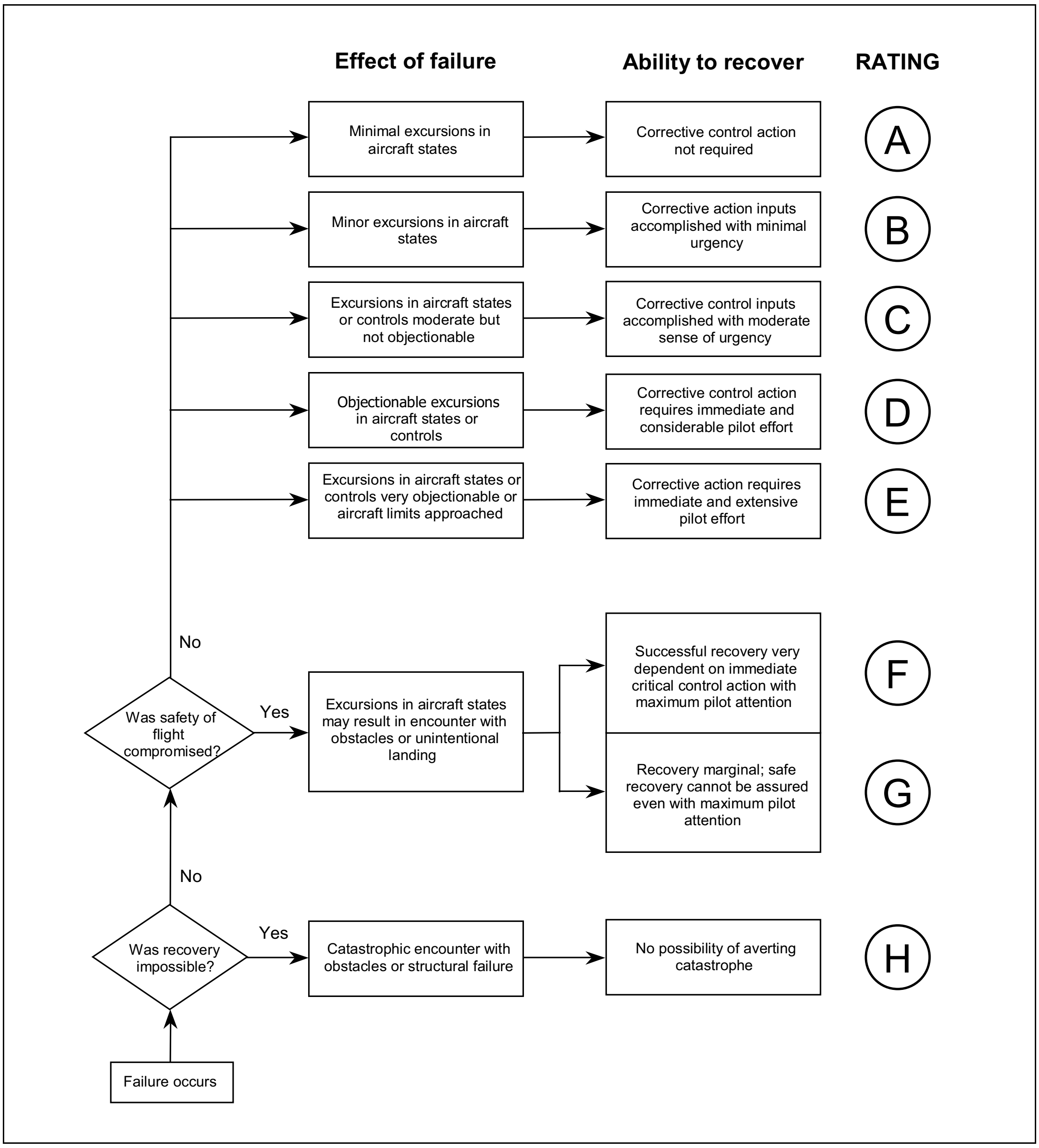

Figure 6-2 Failure/recovery rating scale

4 Airworthiness requirements trial

4.1 Introduction

The basis for this trial is described in detail in Section 3, which identifies the need for specific handling qualities criteria for helicopter TRFs. The aim of the trial was to develop criteria for helicopter handling qualities which, following a TRF would maximise the chances of safe recovery of the vehicle and, more importantly, the personnel. The trial took place during April 1999 and utilised three pilots (referred to as P1, P2 and P3), and over 33 hours of motion-based, pilot-in-the-loop simulation in addition to desktop/fixed base work-up. The pilots were supplied by WHL, CAA and CHC Scotia Ltd (part of CHC Helicopter Corporation).

4.2 Methodology

4.2.1 **Modified yaw responses**: The ADS-33D criteria (described in Section 3) were used as the basis of defining three directional response configurations (from off-line simulations) corresponding to Level 2, Level 3 and Level 4 handling qualities. The primary ADS-33D criterion of interest was the transient attitude response following a failure as shown in Section 3. These configurations were defined in terms of modified yaw response (MYR). MYRs were defined as multiples of the fin lift curve slope and yaw rate damping normally used in the Lynx model configuration as shown in Table 6-7. As can be seen, the baseline configuration was also referred to as MYR 1.

Table 6-7 Modified yaw response definition

MYR	Fin lift curve slope (%)	Yaw rate damping (%)
1	100	100
2	150	300
3	200	500

The lift curve slope provided variation of speed-dependant yaw stiffness and damping, impacting lateral force and yaw moment in translational flight. Real-life variation in this parameter is minimal, but the same factors applied to fin area would have similar effects, assuming the yaw moment arm remained constant. The direct yaw rate damping term was originally used to improve the damping fidelity of the model at low speed and in the hover. Most helicopter fuselages generate some yaw damping when rotating in the hover, and at low speed due to the effect of main rotor (MR) downwash over the rotating rear fuselage; the more aerodynamic the fuselage vertical profile, the greater the natural aerodynamic damping. 'Blowing' the tail boom to control the flow separation, as in the case of NOTAR designs, can further augment this damping. The MYRs were designed to demonstrate what's necessary, in parametric terms, to achieve different Levels of handling qualities, but it is likely, however, that the yaw damping necessary to achieve even Level 3 handling qualities is probably difficult to achieve in practice. From a yaw rate damping perspective (i.e. for hover/low speed cases), but not yaw stiffness, MYR 2 and MYR 3 are therefore probably unrealistic.

It should be noted that the HP setting was initially about 26° (or maximum available on full left pedal); however, this was later reduced to 21° and then 17° (the latter was the maximum for the QinetiQ Lynx flight trial for safety reasons [5]), in order to improve the chances of recovery and allow exploration of the techniques. The LP setting used was mostly -4° but some runs were conducted using -8°.

4.2.2 **Transient and manoeuvre phases**: The TP TRCF type was given low priority for the transient and manoeuvre phases after work-up revealed benign failure transients, particularly at the mid speed condition. From the combination of remaining test variables described in 6.2, there were 27 possible test points for these phases. However, not all of the conditions were taken forward into the manoeuvre flight phase, due to time constraints, the need to prioritise on the boundary cases between controllable and uncontrollable, and those cases where transient stabilisation was unsuccessful.

4.2.3 **Landing phase**: Following a mid-range (TP) TRCF, there will always be a powered trim condition at which the aircraft will be stable and from which a landing can be attempted. Regardless of the trim position of the TR post failure, it will be appreciated that the aircraft must depart from this condition in order to effect the landing. Therefore, despite their low priority in the transient and manoeuvre phases, cases involving TP TRCF were included in the landing phase (the transient phase was instigated but not rated). The combinations of three MYRs and four TRF types gave 12 possible test points; again the TRF initiation was conducted from a nominal initial altitude of 3000 ft.

4.3 Results

The test points carried out for TRDFs, and HP, LP and TP TRCFs are shown in Table 6-8 to Table 6-11 respectively, which show paragraph cross-references where detailed time histories and pilot ratings are provided. A representative selection only of the full results is provided in the interests of brevity. Summary pilot ratings are also provided for most tests in the following paragraphs. Overall there were 29 configuration/speed/TRF combinations flown over 60 test points (i.e. 2 TRF phases being covered on average), each of which was carried out 2.4 times on average.

Table 6-8 Airworthiness requirements trial TRDF test points

Speed	TRF phase	Configuration	Test pt.	No. tests	No. pilots	Paragraph
High	Transient	MYR 1	1	3	3	6.4.4.1
		MYR 2	2	3	2	6.4.4.1
		MYR 3	3	3	3	6.4.4.1
High	Manoeuvre	MYR 1	1	1	1	
		MYR 2	2	2	2	
		MYR 3	3	3	3	
Mid	Transient	MYR 1	4	2	2	
		MYR 2	5	2	2	
		MYR 3	6	2	2	
Mid	Manoeuvre	MYR 1	4	2	2	
		MYR 2	5	2	2	
		MYR 3	6	2	2	
Hover	Transient	MYR 1	7	3	2	6.4.4.2
		MYR 2	8	2	2	6.4.4.2
		MYR 3	9	2	2	
Hover	Manoeuvre	MYR 1	7	1	1	
		MYR 2	8	1	1	
-	Landing	MYR 1	28	2	2	
		MYR 2	29	2	2	
		MYR 3	30	2	2	
Total number of tests:				42		

Table 6-9 Airworthiness requirements trial HP TRCF test points

Speed	TRF phase	Configuration	Test pt.	No. tests	No. pilots	Paragraph
High	Transient	MYR 1	10	3	2	6.4.5.1
		MYR 2	11	2	2	6.4.5.1
		MYR 3	12	3	2	6.4.5.1
High	Manoeuvre	MYR 1	10	3	2	
		MYR 2	11	4	2	
		MYR 3	12	3	2	
Mid	Transient	MYR 1	13	2	2	
		MYR 2	14	2	2	
		MYR 3	15	2	2	
Mid	Manoeuvre	MYR 1	13	2	2	
		MYR 2	14	2	2	
		MYR 3	15	2	2	
Hover	Transient	MYR 1	16	4	2	
		MYR 2	17	1	1	
		MYR 3	18	6	3	
Hover	Manoeuvre	MYR 1	16	4	2	
		MYR 3	18	5	3	
-	Landing	MYR 1	31	4	2	
		MYR 3	33	6	3	
Total number of tests:				60		

Table 6-10 Airworthiness requirements trial LP TRCF test

Speed	TRF phase	Configuration	Test pt.	No. tests	No. pilots	Paragraph
High	Transient	MYR 1	19	2	2	
		MYR 2	20	1	1	
		MYR 3	21	2	2	
High	Manoeuvre	MYR 1	19	2	2	
		MYR 2	20	1	1	
		MYR 3	21	2	2	
Mid	Transient	MYR 1	22	2	2	
		MYR 2	23	1	1	
		MYR 3	24	3	3	
Mid	Manoeuvre	MYR 1	22	2	2	
		MYR 2	23	1	1	
		MYR 3	24	3	3	
Hover	Transient	MYR 1	25	2	2	
		MYR 3	27	2	2	
Hover	Manoeuvre	MYR 1	25	2	2	
-	Landing	MYR 1	34	5	2	
		MYR 2	35	1	1	
		MYR 3	36	5	2	
Total number of tests:				39		

Table 6-11 Airworthiness requirements trial TP TRCF test points

Speed	TRF phase	Configuration	Test pt.	No. tests	No. pilots	Paragraph
-	Landing	MYR 1	37	2	2	6.4.7
		MYR 2	38	1	1	
		MYR 3	39	2	2	
Total number of tests:				5		

4.4 TRDFs

4.4.1 **Forward flight**: The variations in control and response variables during a high speed TRDF for configuration MYR 1 are shown in Figure 6-3. All plots for the transient phase show timescale in seconds where zero is the point of failure. The collective pitch was reduced to zero very rapidly after 2.12 seconds; nevertheless, within the 2 second PIT, the yaw rate built up to a peak of about 60° s^{-1}, with sideslip exceeding the 140 kn Operational Flight Envelope (OFE) limit. The dihedral effect of the MR (rolling moment due to sideslip) overcame the roll attitude hold in the Automatic Flight Control System (AFCS) and rolled the helicopter to starboard by about 70°. Coupled with the reduced collective pitch, flow up through the MR was increased and gave rise to a rapid increase in MR speed to more than 150% of nominal, well in excess of the transient limit. The associated increase in MR thrust produced a deceleration of more than 2g in the flight direction, the forward speed washing off to about 90 kn in about 2 seconds and the aircraft actually climbing during the transient. During some of the runs with this configuration, the pilots were so overwhelmed by the magnitude of the transients and the subsequent disorientation that they returned Level 4 ratings such as 9G for the case shown. In this case engine shutdown was not performed, evidenced by the reintroduction of MR torque; only when the engines were immediately shut down were improved Level 2 and Level 3 ratings given, the best being 6F from P2.

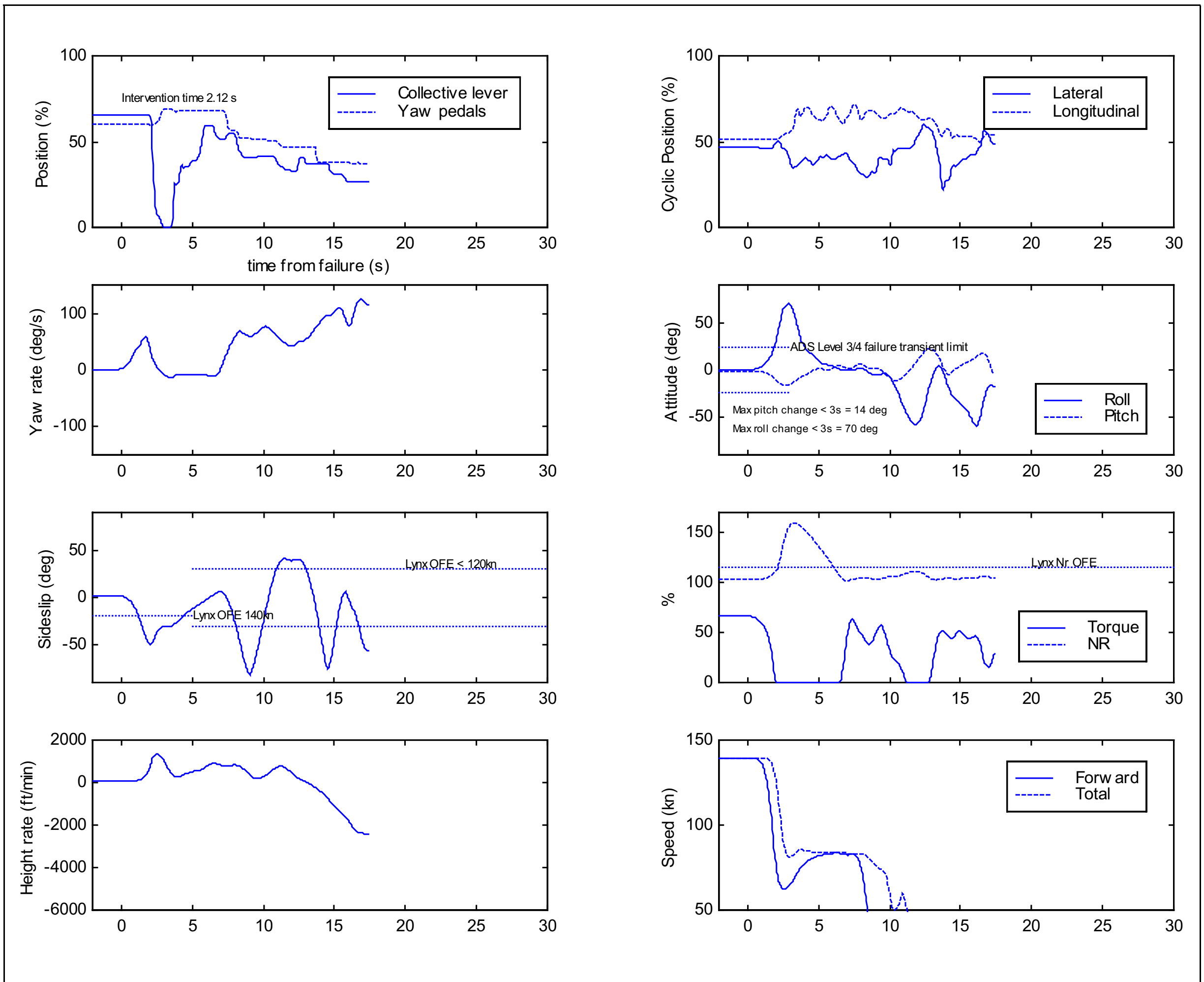

Figure 6-3 Time histories for transient phase of TRDF at high speed (P3, MYR 1)

A number of points need to be made concerning the behaviour of the aircraft during these TRDF transients. First, the sideslip increase to significantly beyond 50° may well have caused structural damage to the rear fuselage. Second, the MR overspeed would also have resulted in very high stresses in the MR system, again causing structural damage. Third, and most important from a modelling perspective, significant areas of the MR disc would have stalled as the MR speed increased, thus acting as a natural brake, reducing the thrust and slowing the MR. The simulation model used in the trial did not include sufficient detail to represent these effects; it is questionable, therefore, whether the MR limits would have been exceeded by such large margins in reality. In the trial the test pilots were briefed to disregard potential structural limit exceedances for this reason.

A similar case using configuration MYR 2 is shown in Figure 6-4. The yaw rate increased to about 25° s^{-1} before the pilot intervened, with the sideslip peaking at the 140 kn OFE boundary. The pilot elected to only reduce collective to about 40% of maximum and the roll attitude just exceeded the ADS Level 3/4 attitude transient (24°). More significantly, with power still driving the MR, the combined pitch/roll response was insufficient to cause overspeeding – the MR speed remained within the governed range. Speed reduction was only about 10 kn. In this case the more effective fin removed the requirement for engine shutdown to be part of the time critical actions and allowed some power to be retained beneficially; a Level 2 rating of 4F was awarded.

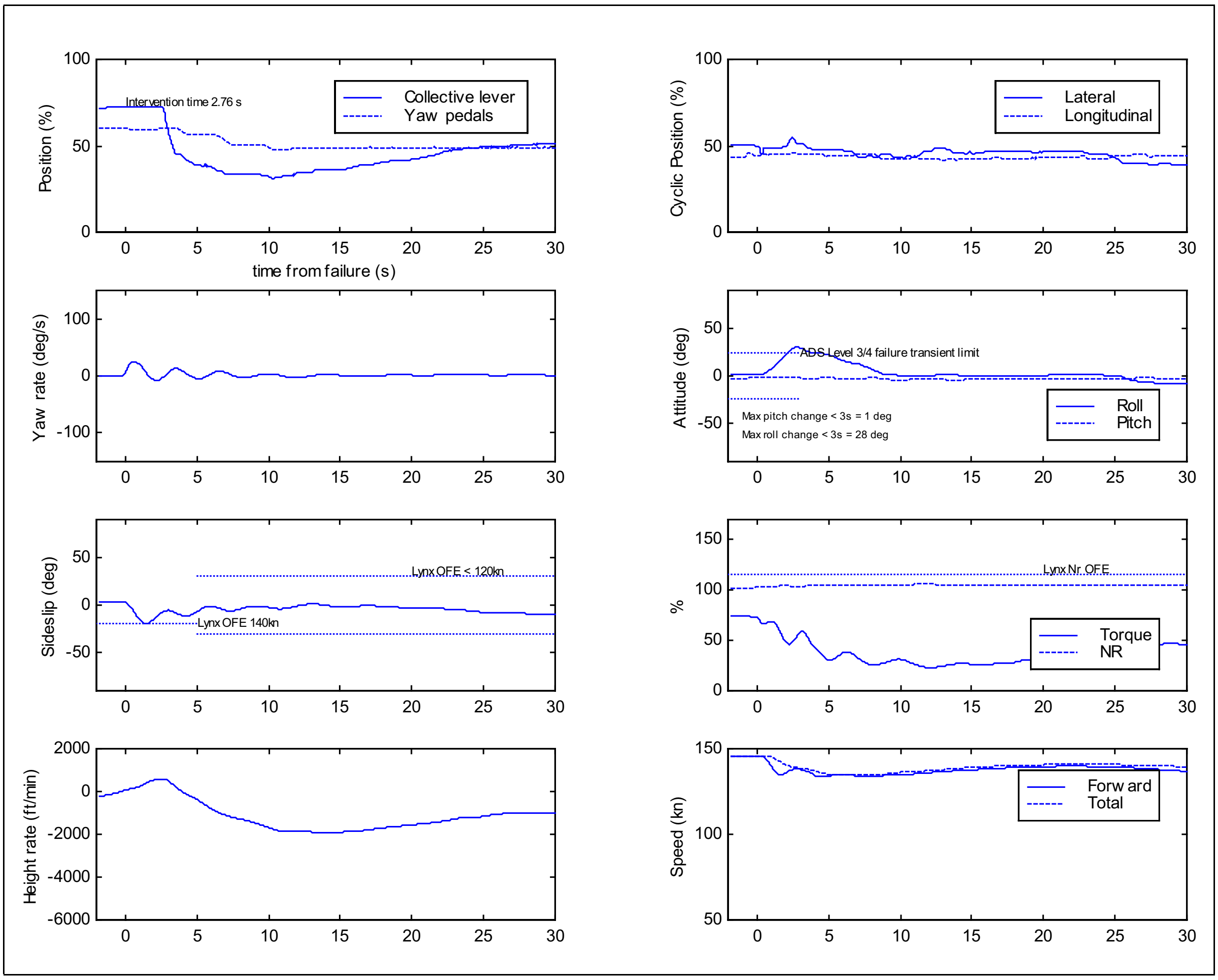

Figure 6-4 Time histories for transient phase of TRDF at high speed (P1, MYR 2)

A further example, using configuration MYR 3 is shown in Figure 6-5. All motions are benign even with the pilot delaying intervention for 3 seconds and a Level 2 rating of 4C was awarded. Again the engines were not shut down.

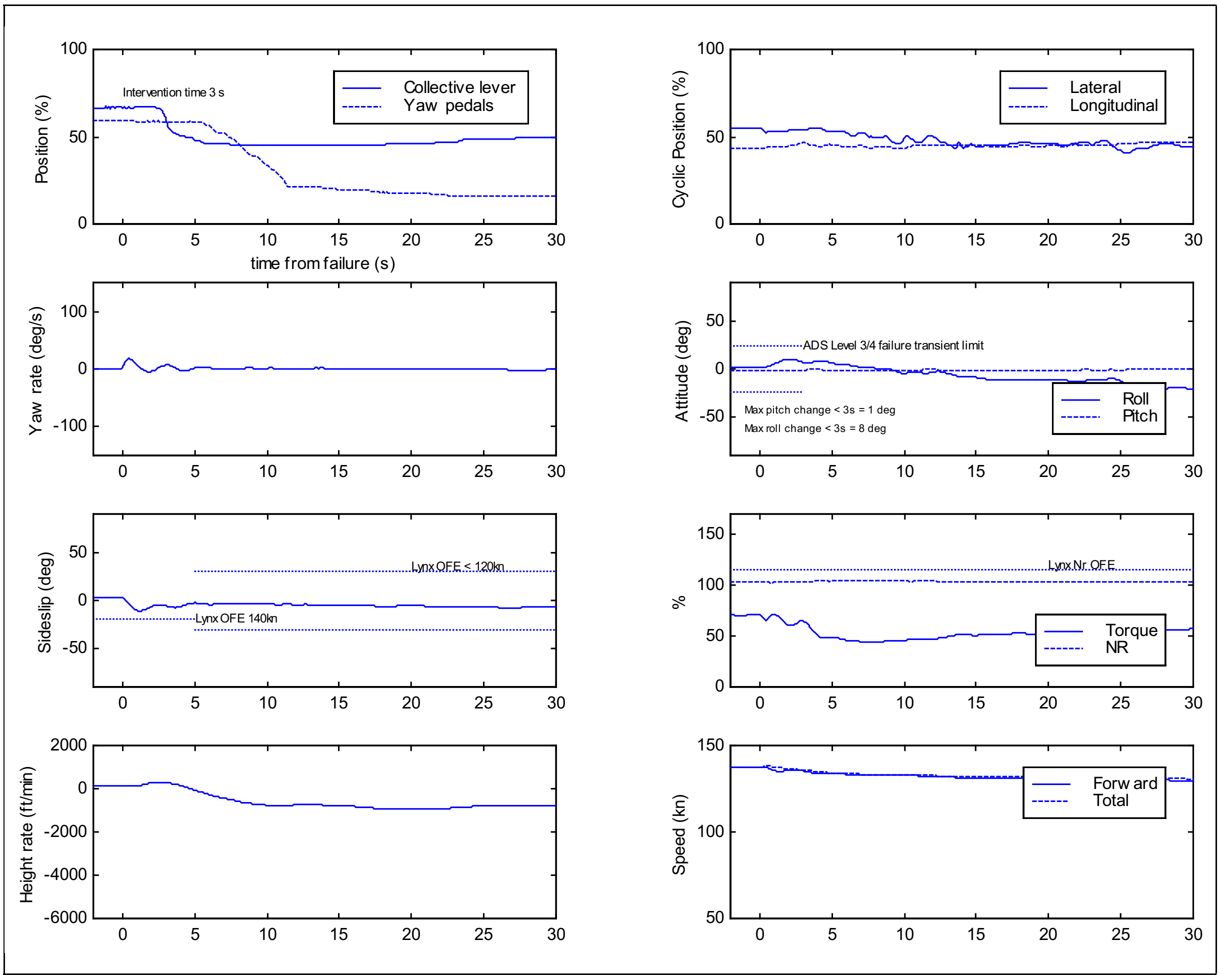

Figure 6-5 Time histories for transient phase of TRDF at high speed (P2, MYR 3)

Height lost during the TRDFs varied between 200 and 600 feet depending on the collective control strategy used by each of the pilots.

The range and average of pilot ratings for the TRDF transient phase at high speed are shown in Figure 6-6 as a function of MYR. Doubling the aerodynamic stiffness from MYR 1 to MYR 3 resulted in a significant proportion of the anti-torque moment being provided by the fin, and the dramatic effect of this and the more powerful restoring moment following the failure is clear. Average pilot HQRs improved from Level 3 to borderline Level 1/2; FRRs improved from G to C. Much of this improvement was actually achieved with the 50% increase in fin stiffness (MYR 1 to MYR 2).

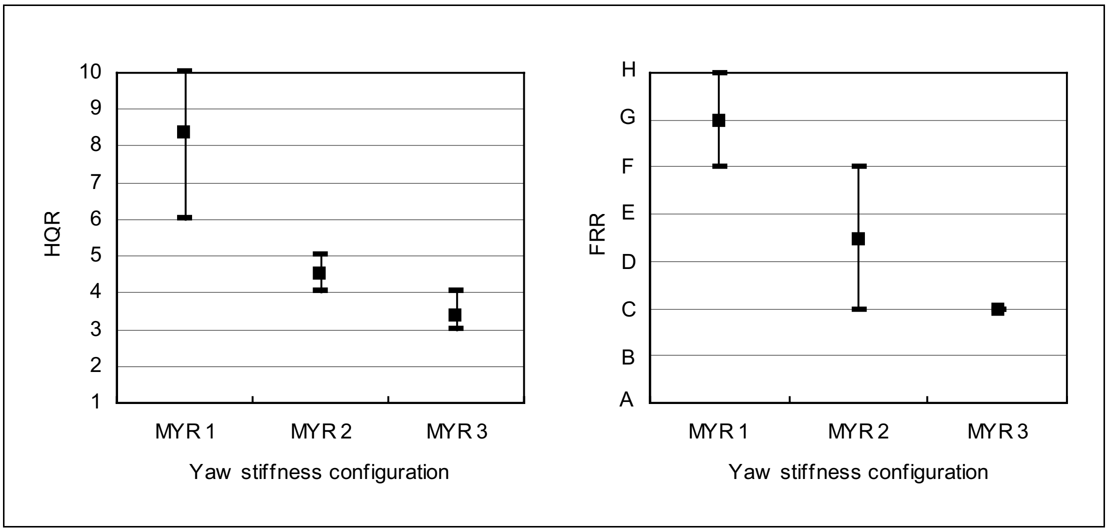

Figure 6-6 Pilot ratings for transient phase of TRDF at high speed

The mid speed ratings shown in Figure 6-7 show similar values (though the improvements are less stark), except that the baseline MYR 1 configuration had a more benign failure characteristic at this flight condition.

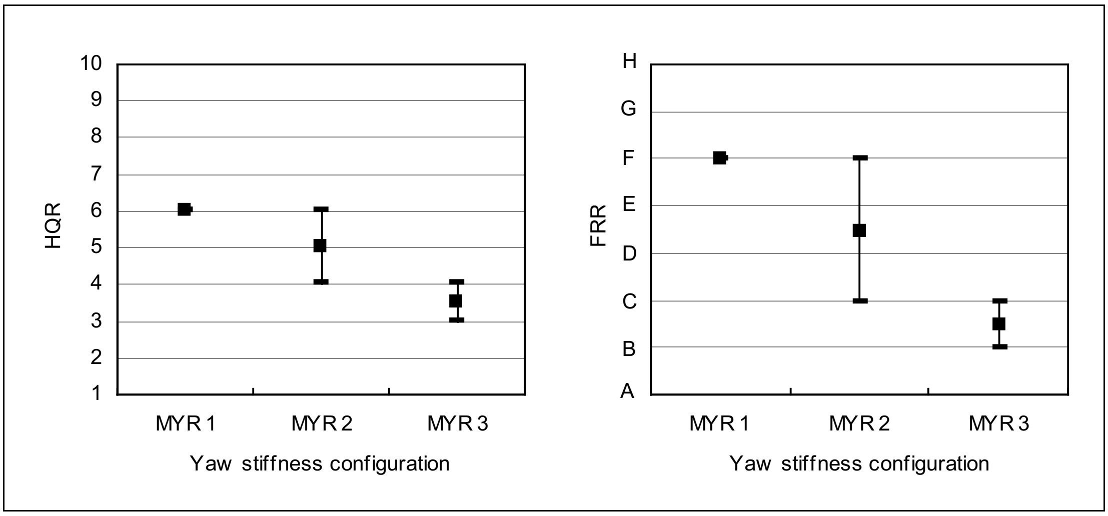

Figure 6-7 Pilot ratings for transient phase of TRDF at mid speed

The pilot ratings awarded for the manoeuvring and landing phases following a mid speed TRDF are shown in Figure 6-8 and Figure 6-9 respectively. In practice, it was found that the aircraft decelerated to this mid-speed, even after failures at high speed, so that the results for both phases are also applicable to the failures at high speed. The baseline MYR 1 configuration gave Level 3 handling qualities, the MYR 2 configuration is Level 2 and the MYR 3 configuration is borderline Level 1/2.

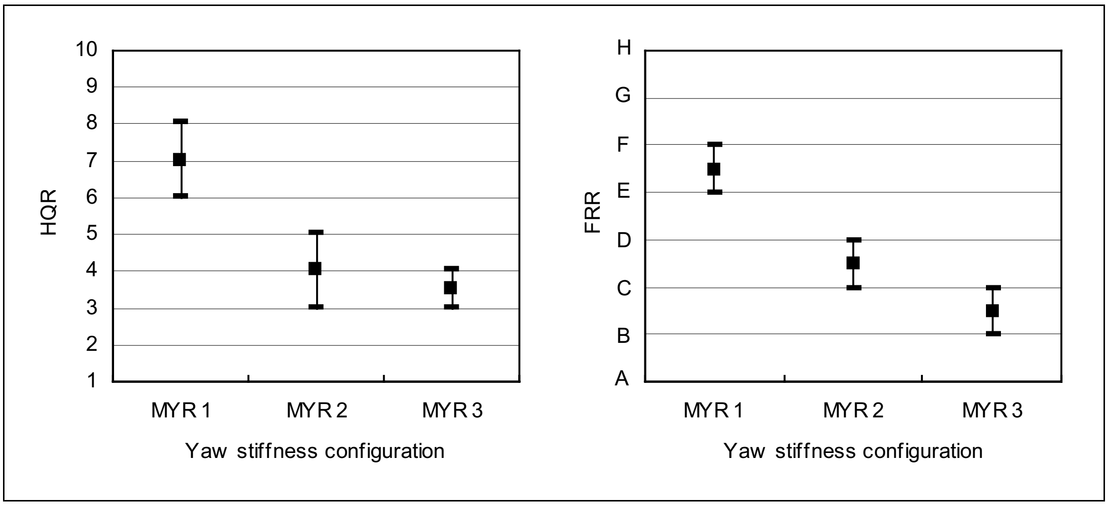

Figure 6-8 Pilot ratings for manoeuvre phase of TRDF at mid speed

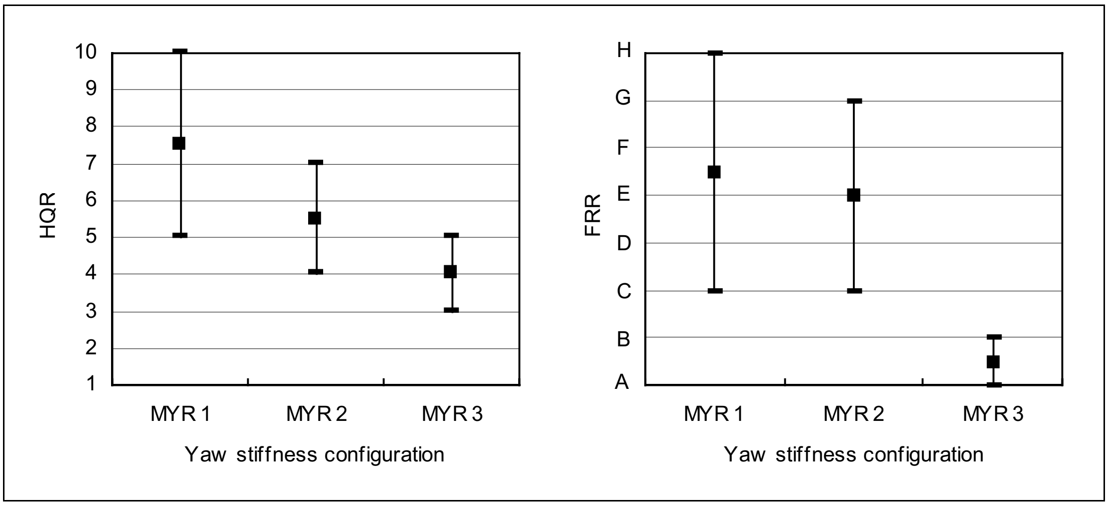

Figure 6-9 Pilot ratings for landing phase of TRDF at mid speed

As far as the ability of the pilot to recover from a TRDF at typical cruising speeds and altitudes is concerned, the results suggest that with a PIT of 2 seconds the following should apply:

- For Level 2 handling qualities, the directional stiffness should be such that the initial transient sideslip peak is less than the OFE limit, or 30° whichever is the smaller.
- For Level 3 handling qualities, the directional stiffness should be such that the initial sideslip peak is less than that causing structural limit loads to be reached or 60° whichever is the smaller.
- In terms of transient roll response, the combined dihedral effect (which, depending on the type, may be either advantageous or adverse at the transient sideslip peak) and attitude hold function in the AFCS should be such as to contain the roll transient to less than 30° for Level 3 handling qualities and 10° for Level 2.
- There should be no requirement for engine shutdown to be part of the time critical pilot actions.

Generally, the levels of directional stiffness which gave rise to these handling qualities during the failure transient also gave similar handling qualities during the manoeuvre and landing phases.

4.4.2 **Hover**: These cases were all in the high hover (3000 ft) and landing was not considered. Note that for the hover cases, and the landing phase for all cases, the lateral velocity time history is presented alongside that of sideslip. The response of the baseline MYR 1 configuration to TRDF in the high hover is shown in Figure 6-10. The pilot intervened at about 2.5 seconds when the yaw rate had increased to over 150° s^{-1}, and struggled to control the aircraft for nearly 30 seconds while descending over 2000 ft, but was unable to reduce the gyratory motions in pitch and yaw. In the final 10 seconds of the manoeuvre the pilot held the cyclic against the forward stop while the aircraft spun with a bank attitude of 50° left and a yaw rate of about 100° s^{-1}. The pilot had lost control and returned a Level 4 rating of 9H (strictly speaking, loss of control should attract an HQR of 10). With a PIT of 2 seconds there seems to be little that can be done in the baseline configuration to avoid the spin entry caused by the TRDF.

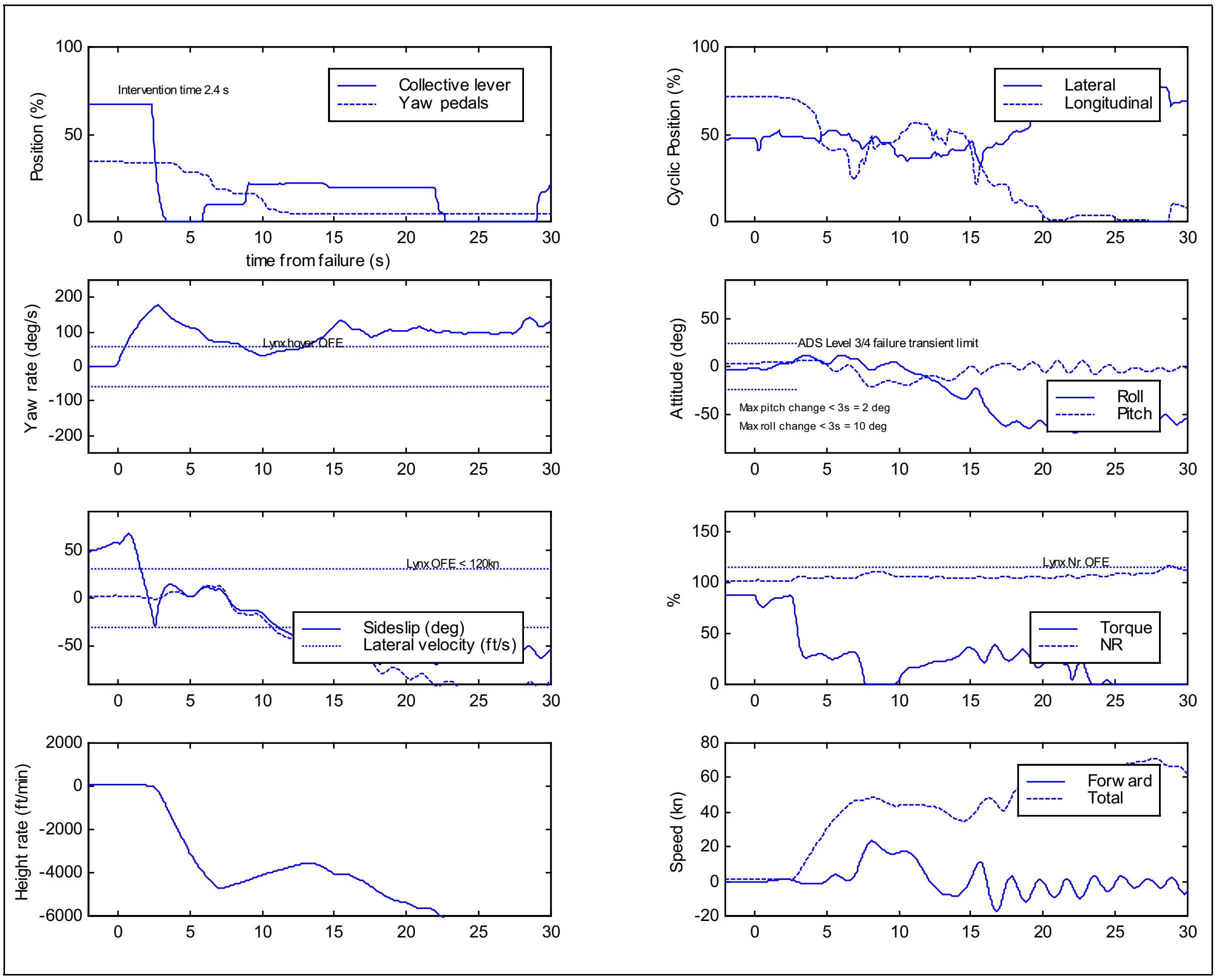

Figure 6-10 Time histories for transient phase of TRDF in the hover (P1, MYR 1)

Figure 6-11 shows the results when the fuselage yaw damping was increased threefold to MYR 2, the increment found to be required for the pilot to return Level 2 ratings (in this case 5E). The PIT for this case was actually as high as 3.4 seconds, when the pilot reduced collective to zero, containing the yaw rate peak to about 120° s^{-1}. The pilot pushed the stick forward, and pitched and rolled into the turn. The yaw rate reduced to zero after about 10 seconds with the aircraft accelerating through 40 kn and descending at more than 4000 ft/min. Collective was reintroduced after 12 seconds but torque and yaw rate remained at zero due to the engines having been shut down. After 30 seconds the aircraft had settled into autorotation at about 80 kn with a descent rate of about 3000 ft/min and height lost of over 1300 ft.

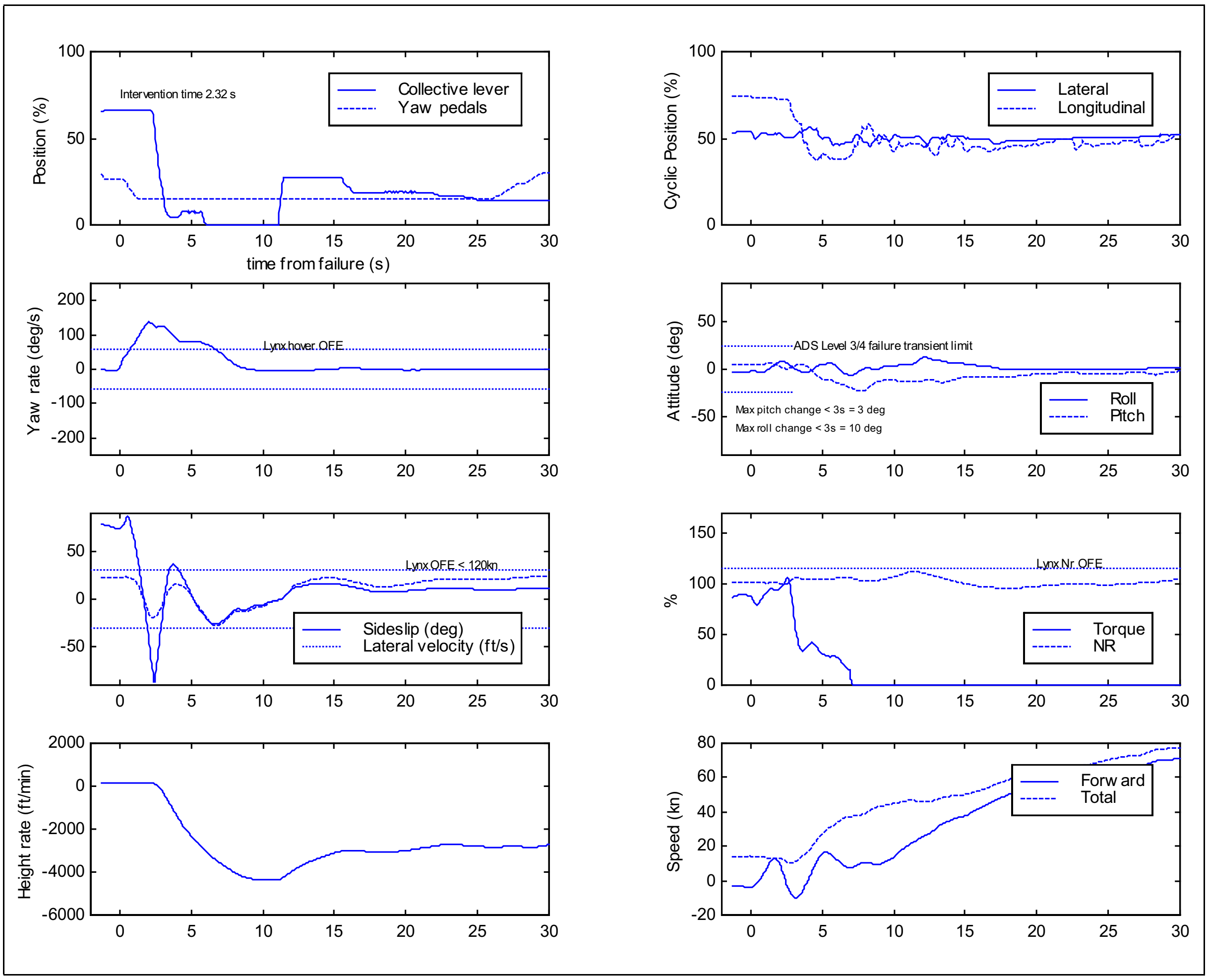

Figure 6-11 Time histories for transient phase of TRDF in the hover (P1, MYR 2)

The summarised pilot ratings for the hover TRDFs are shown in Figure 6-12. The results from this investigation suggest that to recover from a TRDF in the hover (assuming height is available) with Level 2 handling qualities, the yaw rate transient peak should be less than 120° s^{-1} (or the OFE limit, whichever is the lower), following a 2 second PIT. This result is very tentative, because only a limited number of runs were undertaken. The ability of the pilot to recover from the initial spin, and avoid entry into an even more severe flat spin by increasing forward speed, is likely to depend on the detailed aerodynamic characteristics of the fuselage and empennage (i.e. type-specific). Their interactions and the functionality of the AFCS in the pitch and roll channels will also influence the results. More work is required to firmly establish what rate of yaw transient defines the Level 2/3 boundary.

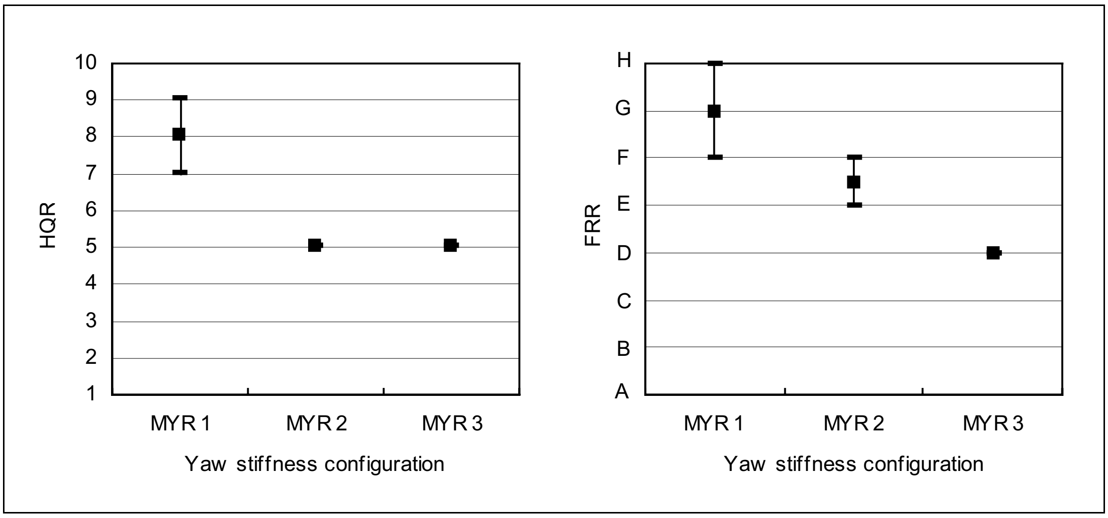

Figure 6-12 Pilot ratings for transient phase of TRDF in the hover

4.5 HP TRCFs

4.5.1 **Forward flight**: Results for the baseline MYR 1 configuration during a high speed HP (26°) TRCF are shown in Figure 6-13. The TR pitch time histories are shown as a percentage, where 0% and 100% represent maximum (left pedal) and minimum (right pedal) pitch attainable overall; the pitch angle itself is annotated. The TRCF was gradually applied over a duration of 4 seconds. There was no dramatic build-up of yaw rate and sideslip as was seen with the 1 second TRDF onset. The pilot intervened after 3 seconds and rolled the aircraft towards the sideslip to re-trim the aircraft. The sideslip built to 40°-50° with similar levels of roll angle after about 15 seconds into the failure. The pilot had reduced collective by about 10% and was attempting to re-trim the aircraft in a high speed descent. Despite the apparently straightforward recovery, the pilot awarded Level 3 handling qualities (7F). The problem was that the pilot had great difficulty decelerating the aircraft into a condition where manoeuvring was possible. Any attempt to reduce speed by lowering collective and pulling back on the cyclic resulted in the sideslip diverging. Although speed reduction was actually better achieved with MYR 1 (Figure 6-13) than with MYR 2 or MYR 3 (see Figure 6-14 and Figure 6-15), this was at the expense of higher sideslip, roll angle and descent rate, and increased control activity. The pilots in this trial did attempt to recover from the failure using the ‘climbing turn’ recovery technique advocated during the Lynx TRF investigation [5], but with only limited success. Turns to the right were virtually impossible with the high TR thrust opposing the motion.

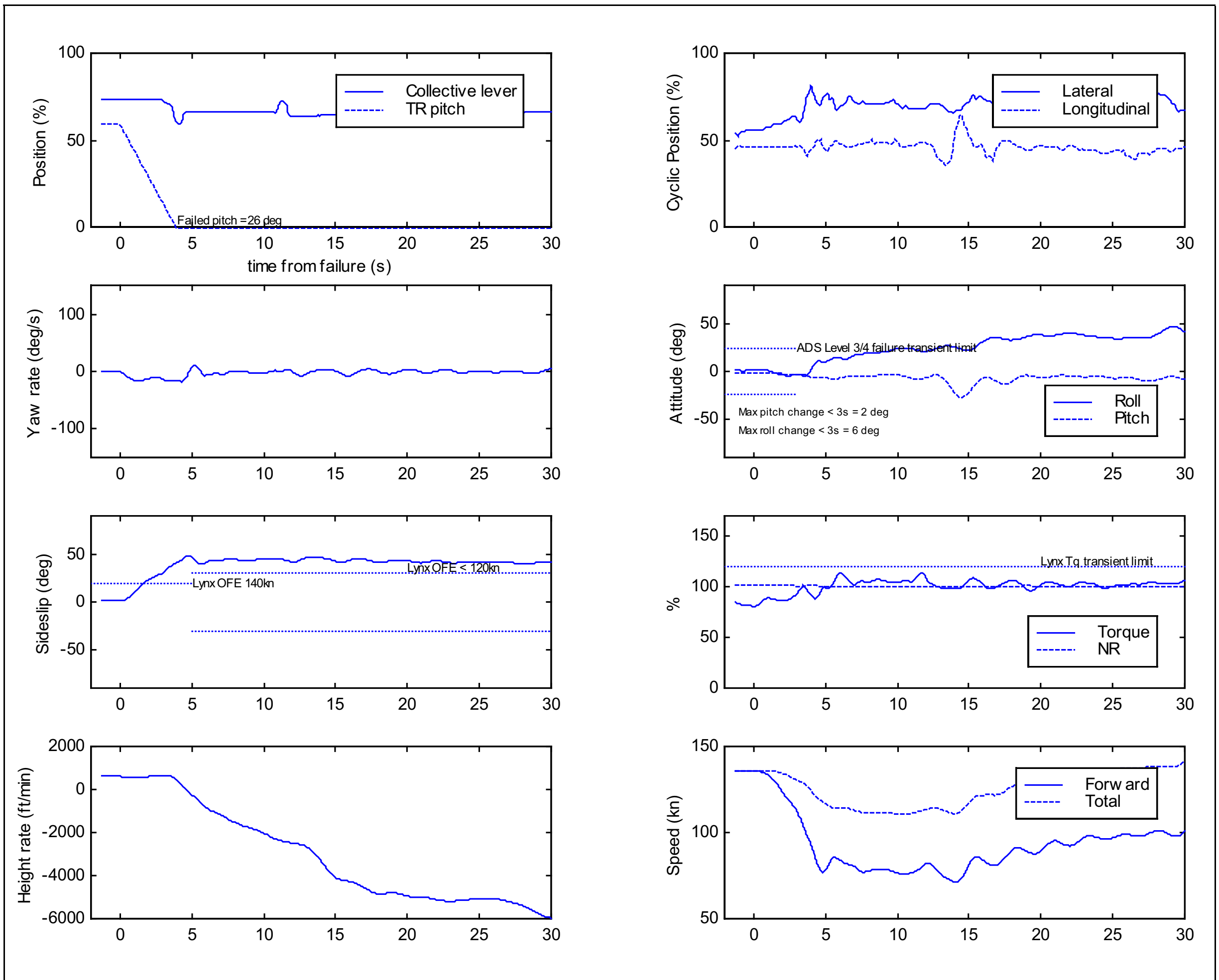

Figure 6-13 Time histories for transient phase of HP TRCF at high speed (P2, MYR 1)

Figure 6-14 and Figure 6-15 show similar recoveries with configurations MYR 2 and MYR 3 using the same TR pitch angle and returning ratings of 5D and 4C respectively. The aircraft remained in the high speed condition in both cases however, with sideslip and roll settling at about 20° and 30° respectively; the pilot is again unable to decelerate through to lower speed, high power conditions.

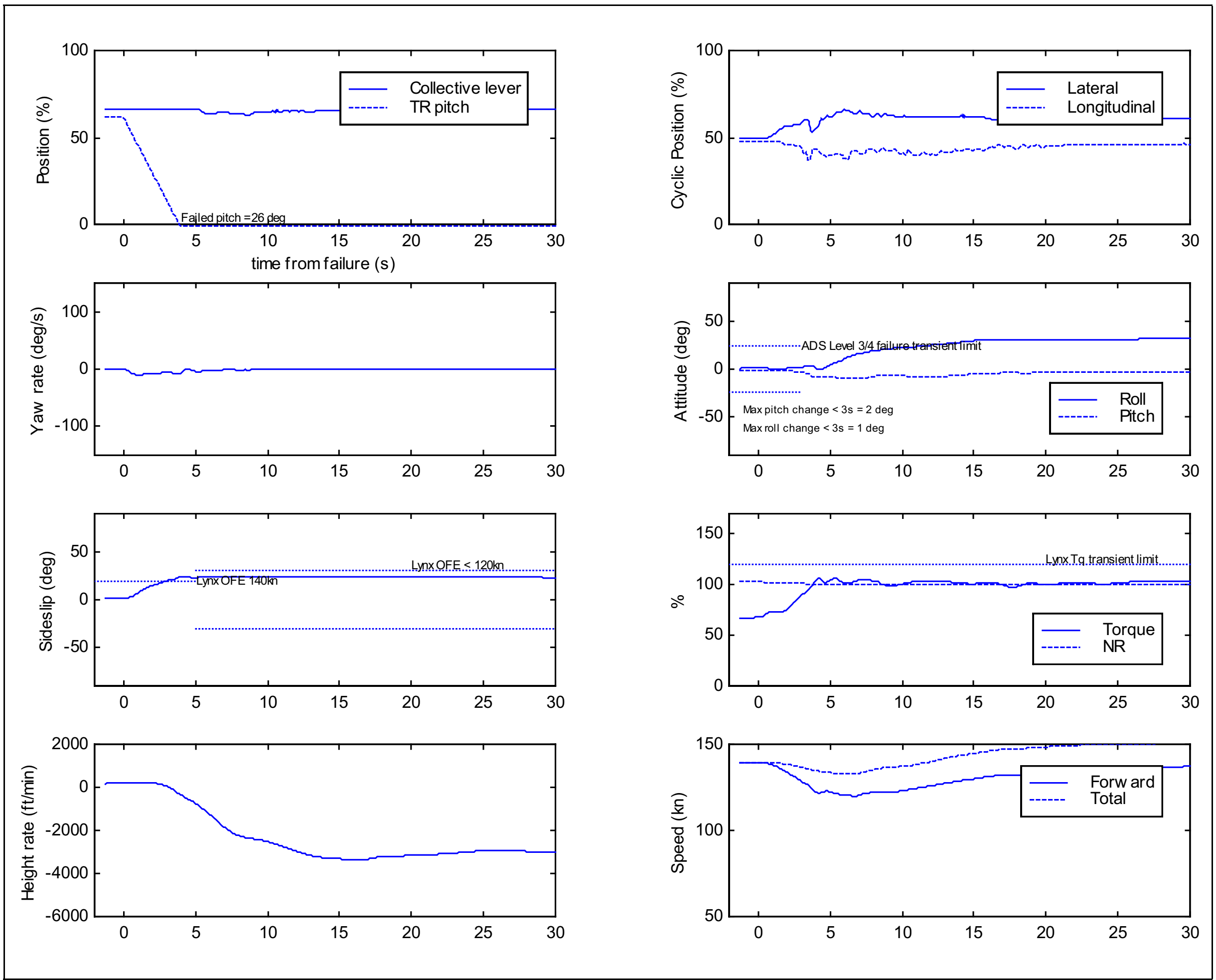

Figure 6-14 Time histories for transient phase of HP TRCF at high speed (P1, MYR 2)

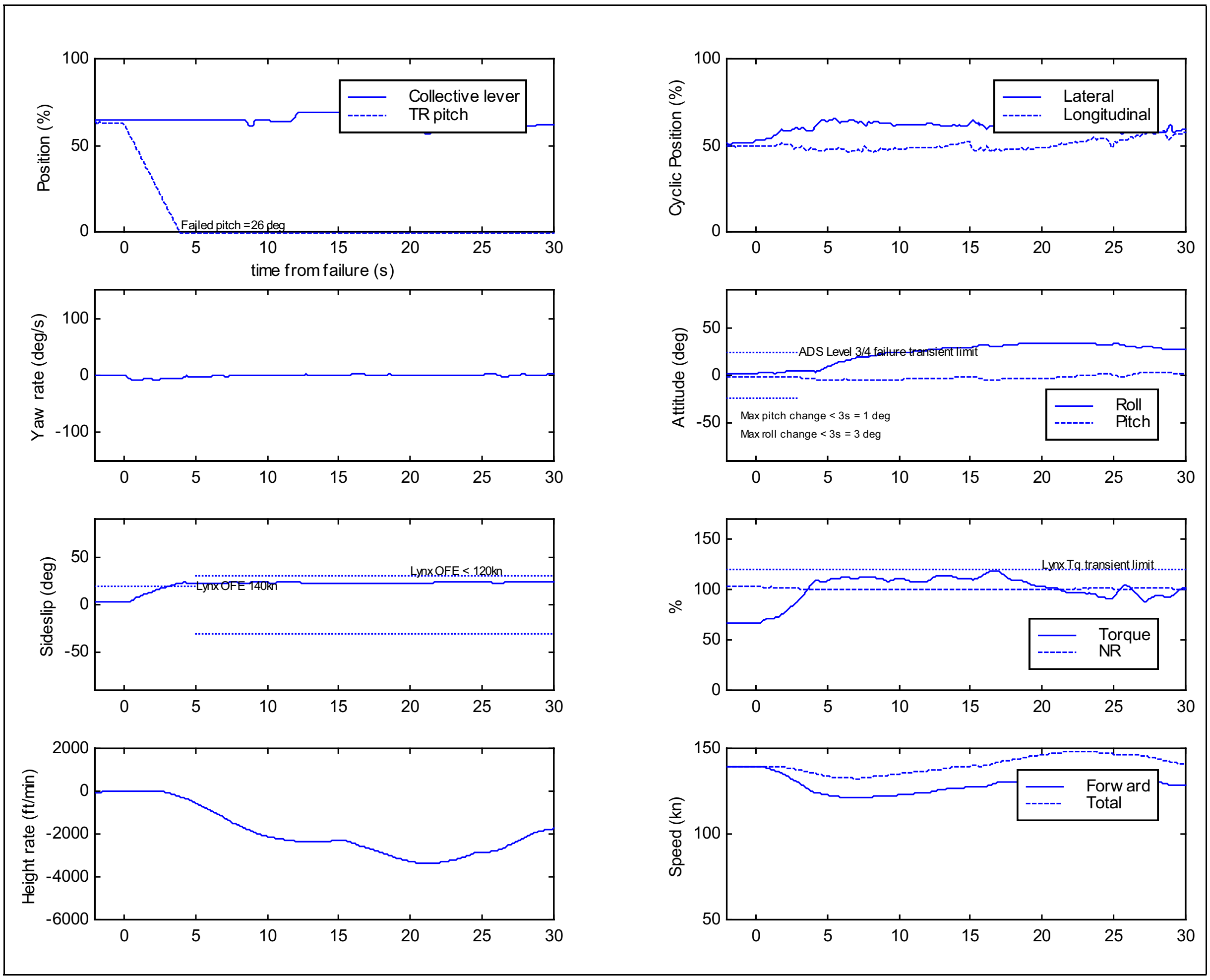

Figure 6-15 Time histories for transient phase of HP TRCF at high speed (P1, MYR 3)

Figure 6-16 shows the pilot ratings for the 26° HP TRCF mid speed manoeuvre phase. The pilots returned borderline Level 2/3 ratings, indicating that turns in both directions could be accomplished just within the adequate standards.

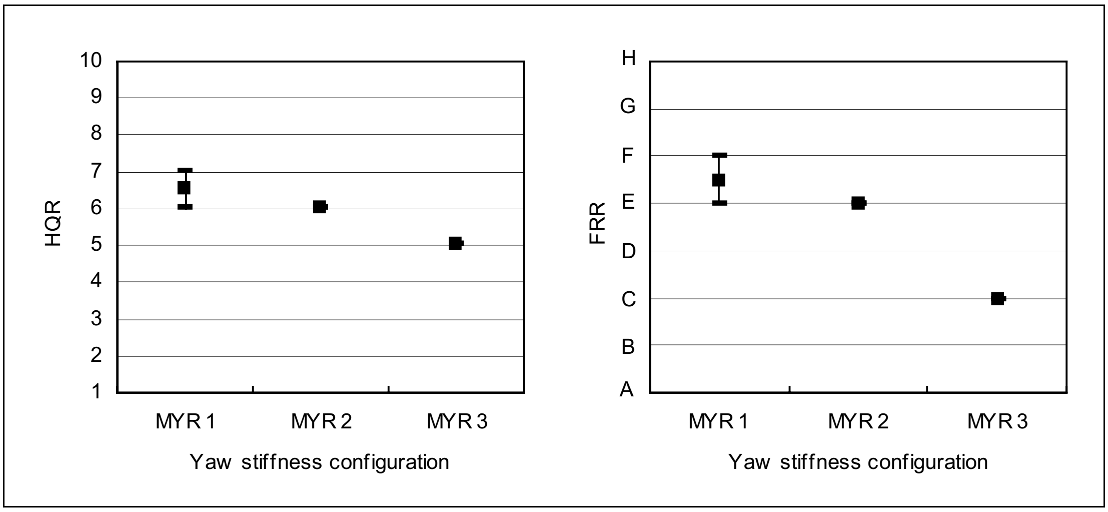

Figure 6-16 Pilot ratings for manoeuvre phase of HP TRCF at mid speed

4.5.2 **Hover**: Figure 6-17 shows the pilot ratings awarded for the 26° HP TRCFs in the hover flight condition. The pitch failed over a 4-second period leading to a build-up in left yaw. After 5 seconds the yaw rate was greater than 100° s^{-1}. The pilot could not manoeuvre out of this spin condition and returned a Level 4 rating (9G). Configuration MYR 3 was necessary to return Level 2 ratings (5-6E).

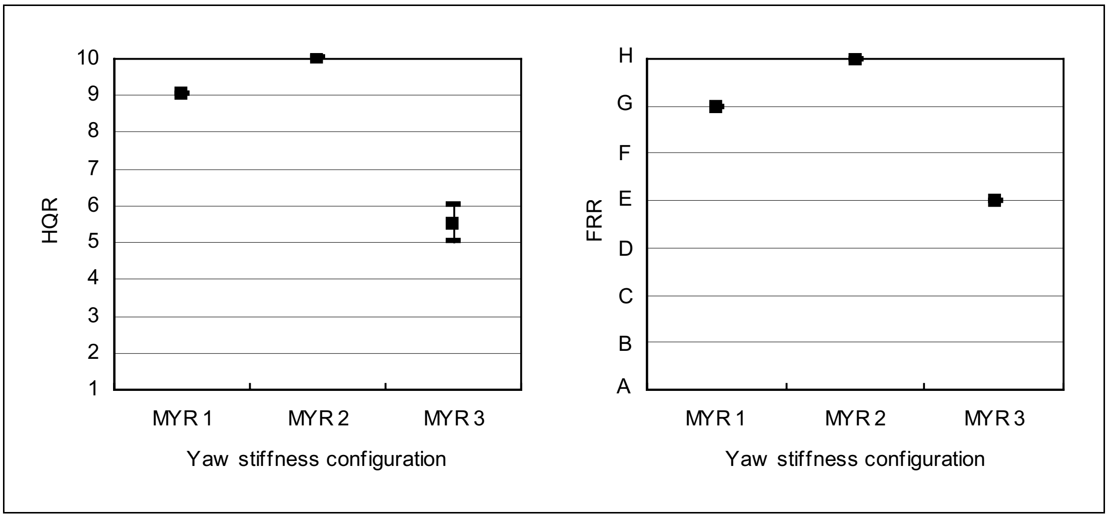

Figure 6-17 Pilot ratings for transient phase of HP TRCF in the hover

Recovery from HP TRCFs in both forward flight and in the hover was very difficult; although not shown here, the ability to manoeuvre away from the failure condition and land was always questionable. The most general conclusion that can be made is that HP TRCFs lead to severely degraded handling qualities, which significantly reduces the chances of landing without incurring serious damage and/or injury.

4.6 LP TRCFs

LP TRCFs are similar in some respects to TRDFs, except that the TR continues to provide some yaw stiffness and damping in forward flight and damping in the hover. The pilot rating trends for the different configurations are shown in Figure 6-18, Figure 6-19 and Figure 6-20 for high speed, mid speed and in the hover respectively, using a TR pitch angle of -4°. Only in the hover, with the baseline MYR 1 configuration, did the HQRs degrade into Level 3, although the FRR indicates that recovery was marginally possible. The response characteristics have the same pattern as for TRDFs, although generally more benign. Although there was less coverage of the LP TRCF test points in this trial, it is considered appropriate to draw the same handling qualities conclusions as for the TRDFs.

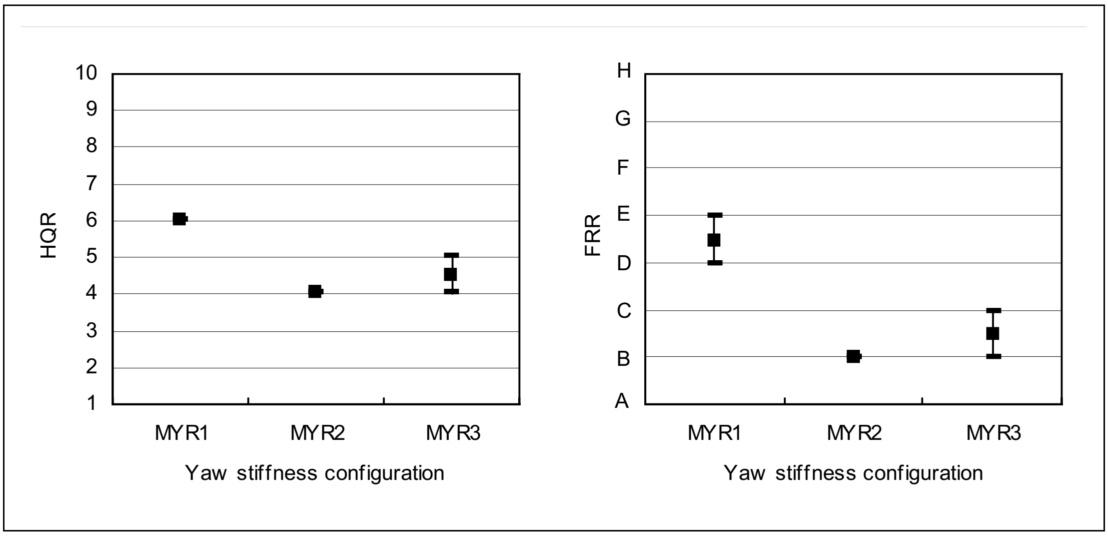

Figure 6-18 Pilot ratings for transient phase of LP TRCF at high speed

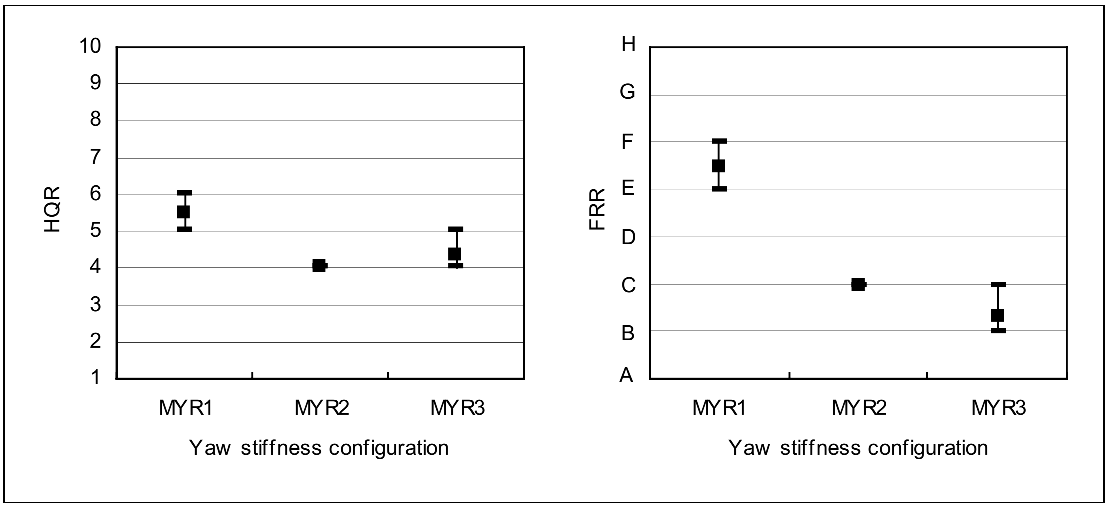

Figure 6-19 Pilot ratings for transient phase of LP TRCF at mid speed

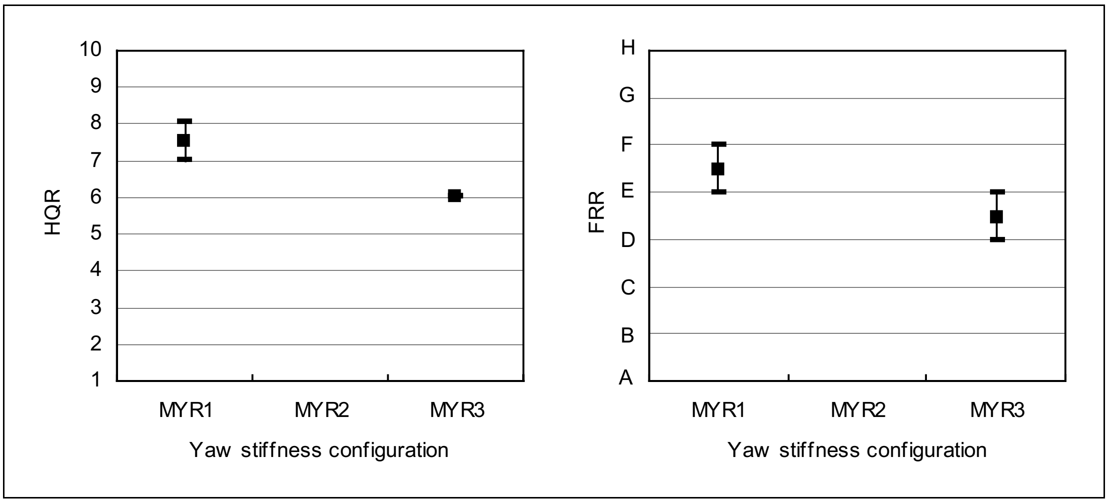

Figure 6-20 Pilot ratings for transient phase of LP TRCF in the hover

4.7 TP TRCFs

Example time histories for a TP TRCF at mid speed using configuration MYR 1 are given in Figure 6-21. The TRCF and data logging were initiated when the altitude had reduced to around 500 ft, and the time scale is shown in seconds with zero at the point of touchdown. Both transient and landing phases are shown, but ratings were only recorded for the landing phase, in this case 3B equating to Level 1 handling qualities. The transient phase was benign with sideslip and yaw rate magnitudes remaining within 20° and 5° s^{-1} respectively. Control activity was minimal and a stable powered run-on landing was achieved at 50 kn. It is clear that this type of failure is very benign compared to TRDF and other types of TRCF covered in earlier parts of this section.

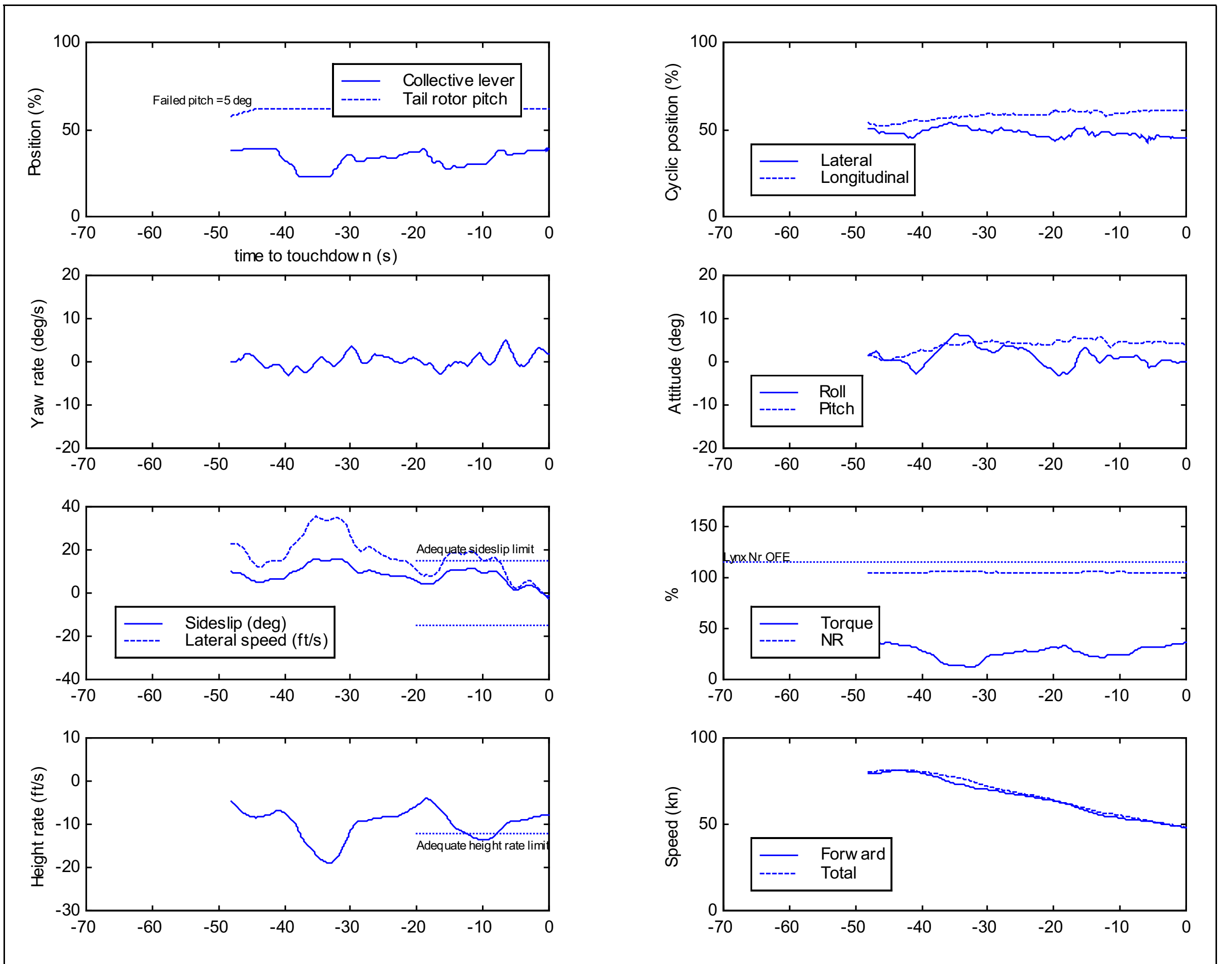

Figure 6-21 Time histories for TP TRCF at mid speed (P1, MYR 1)

The pilot ratings for the various TP TRCF configurations are shown in Figure 6-22. There was no overall improvement gained from increased fin stiffness and damping. Attempts were made to decrease the landing speed to 40 kn but this was at the expense of increased sideslip and yaw rate at touchdown. The pilots commented that the higher yaw stiffness was almost working against them.

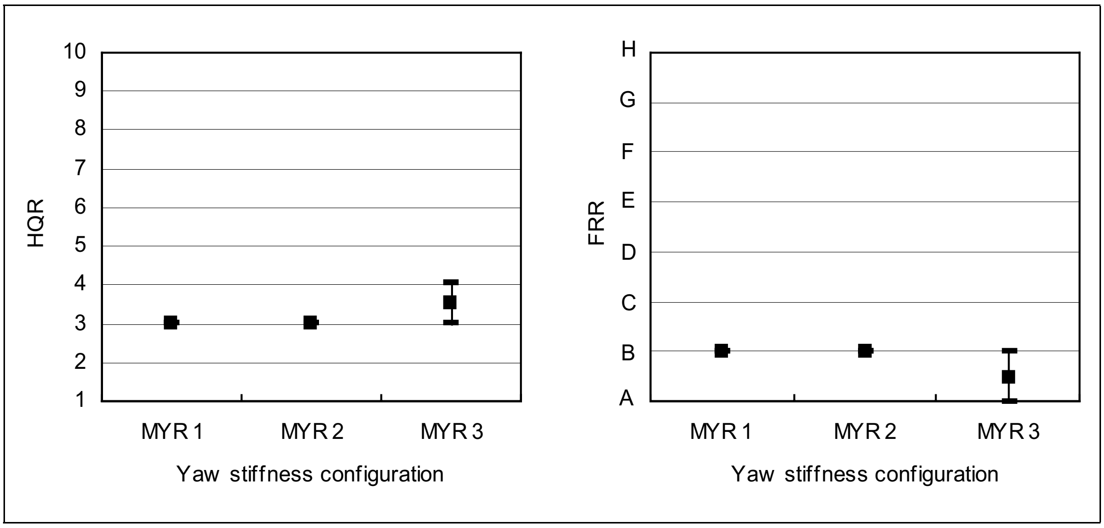

Figure 6-22 Pilot ratings for landing phase of TP TRCF

5 Mitigating technologies trial

5.1 Introduction

This trial examined a selection of proposed TRF mitigating technologies to investigate compliance and practicality of the solutions, with regard to the airworthiness requirements developed during the first trial reported in 4. The aim of the trial was to evaluate different forms of mitigating technology which, following a TRF, could maximise the chances of safe recovery of the vehicle and personnel. The trial took place in June 1999 and utilised two pilots (P2 and P3 as used in the first trial) and almost 14 hours of motion-based, pilot-in-the-loop simulation in addition to desktop/ fixed base work-up. The pilots were supplied by CAA and CHC Scotia Ltd.

5.2 Methodology

The following paragraphs describe the systems selected for evaluation. Those described in Section 5 were judged on the basis of minimising the complexity/payoff ratio, the likelihood of providing a noticeable effect, and the difficulty and/or appropriateness of simulation. Those not evaluated included twin TRs, fly-by-wire/fly-by-light (FBW/FBL), back-up control systems, duplex hydraulic systems, novel ducted fans, duplex/robust simplex TR drive shafts, variable camber fin and secondary load paths. Some additional items were selected to understand the impact of dimensional variations and design features seen on some current helicopter types. It is appreciated, however, that there are other operational systems not considered here (or in Section 5) such as the active rudder on the T-tail of the MD Helicopters NOTAR types. The baseline model configuration (known as MYR 1 in the first trial) was subject to appropriate parameter changes to effect the various technologies. Most tests were conducted from a nominal initial altitude of 3000 ft, but the HP TRCF tests in the hover were conducted from 50 ft.

5.2.1 **Engine chop switch**: The use of an engine cut-off on the pilot's immediate controls was used during both simulator trials programmes as the method of achieving engine shutdown. Other methods were not attempted, nor were specific delays varied to represent this alone.

5.2.2 **Spring return/SBU/NFG systems**: There are several systems available such as the Spring Bias Unit (SBU) fitted to most UK MOD Lynx, the Negative Force Gradient

(NFG) spring system fitted to UK MOD Sea Kings and Sikorsky S-61s, and the SBU spring return system fitted to UK MOD Puma helicopters and the Eurocopter AS332. These work to either reduce TR control loads in the event of hydraulic system failure and/or to set a predetermined TR pitch setting on control cable failure. In these cases, the control-free equilibrium TR pitch which results is approximately that of the cruise condition, and should thus allow the aircraft to be flown at that condition. The task of bringing that condition about (i.e. managing any transients) from manoeuvring flight has not been covered in this project, and further type-specific studies are recommended. In the first trial, TP TRCF with a TR pitch angle setting specific to the Lynx SBU was covered to provide pilot ratings for the landing phase only, and reference should be made to 6.4.7 for example test results.No further tests of this kind were performed in this second trial.

5.2.3 **Variable tail boom strake**: The tail boom strake concept has been utilised on various helicopters to provide changes to the tail boom side force at hover and low speed, through the circulation generated on the tail boom in the MR downwash, as a general, as opposed to a TRF specific design feature. By varying the strake ‘camber’, or orientation relative to the resultant velocity, the side force can be varied during yawing motions at low speed, thus mitigating against the effects of both TRDF and TRCF. Such a system increases the yaw damping in hover and was to have been implemented in this trial as a simple damping augmentation in hover. However, the damping variations used in configurations MYR 1, MYR 2 and MYR 3 of the first trial had effectively already covered this aspect, and for example test results, reference should be made to the hover cases in 6.4. No further tests of this kind were therefore performed.

5.2.4 **Articulated MR system**: The Lynx has a hingeless MR system with equivalent hinge offset of about 12% of MR radius. To explore the read-across to articulated and other MR systems with lower (actual or effective) hinge offsets, such as the Sikorsky S-76 and Eurocopter Dauphin, a reduction to an equivalent hinge offset to about 4% was performed to examine the impact on the pitch and roll transients during TRFs. This was modelled through a change to the Lynx model MR stiffness parameter.

5.2.5 **Enlarged fin**: Increased fin size, combined with the normal degree of cambering, serves two purposes. First, the increased side force on the fin in the trim condition reduces the TR thrust required to balance the residual moment from the MR torque, and therefore transient yaw moment during a TRDF. Second, during a TRF, the increased directional stability reduces the amount of sideslip transient incurred and hence the magnitude of the transient response following failure. Helicopters equipped with a tail fan (e.g. Fenestron on some Eurocopter types), as opposed to a conventional TR tend to have larger fins accommodating the fan itself. The work reported on in Section 5 noted that some studies had shown very large fin areas to be required to achieve sufficient yaw stiffness and damping during TRF. In order to assess the benefits of a larger fin (the Lynx has a particularly small fin compared to some types), a single configuration, representing a fixed fin using 150% of the baseline fin area, was selected which is realisable from an engineering standpoint and reflects existing types. It is similar to the MYR 2 configuration used in the first trial except that the baseline MYR 1 damping was retained for hover/low speed.

5.2.6 **Deployable fin**: Whilst retaining the baseline fin for normal operations, this technology would allow for reduction of the yaw transients resulting from TRFs in forward flight. The approach taken in this trial was to investigate the potential reductions in yaw transient during the most severe cases of TRDF and HP TRCF at high speed. Full deployment resulted in an enlarged fin identical to the fixed enlarged fin and used a deployment time of 2 seconds, operable any time after the PIT.

5.2.7 **Drag chute**: This device reduces the yaw excursions during TRFs from forward flight conditions. It is not expected to provide much assistance in the hover, however, and this flight condition was awarded a low priority during the trial. The design proposed in [5] was used to evaluate the potential for mitigation. Pilots were required to wait until after the PIT before manual deployment, although once selected, deployment was instantaneous. The diameter used was 5 ft in most cases; too much drag resulted when a diameter of 10 ft was used, although this was attempted for some HP TRCF cases.

5.2.8 **Attitude command/attitude hold response type**: Most civil and military helicopters feature what is described as a rate command/attitude hold response type in pitch and roll. That is, when the pilot moves the cyclic, a rate of pitch or roll is commanded and, during hands-off conditions, the attitudes are held. The Lynx features an attitude command, attitude hold (ACAH) response type in pitch and roll for small amplitude excursions as a design feature in the Automatic Stabilisation Equipment part of its AFCS, and was included in the baseline model configuration. Following a TRF transient, the ACAH system will hold fuselage pitch and roll angles until the AFCS series actuators saturate. During the first trial, there was evidence that the AFCS was able to contain attitude, hence minimising pitch and roll excursions during the failure transients at the mid speed condition, but not at the high speed condition. In this trial the effect of removing the ACAH feature from the Lynx AFCS was examined to quantify the mitigating effect of ACAH following TRDF. Both the attitude command and hold functions were disabled, leaving a rate command (RC) AFCS only; however, since most tests were hands-on, removal of the hold function was not generally important.

5.2.9 **AFCS authority**: The effect of increasing the authority of the AFCS series actuators providing the attitude hold stabilisation function was examined in an attempt to contain the TRF transients. The increase was from the baseline ± 10% to ± 20% of full blade angle throw. The baseline value is typical of most current helicopters, although the Tiger and OH-1 both have 20% yaw authority (irrelevant for TRFs) and the NH-90 is believed to have 25% authority in all axes in its quadruple FBW system.

5.2.10 **Warning device**: To examine the effectiveness of a warning device (such as those desribed in Section 4), PIT was varied in different failure situations and evaluated as follows:

- reduction to 1 second during TRCFs in the hover (with N_R control);
- reduction to 1 second for TRDF at high speed;
- increase to 3-4 seconds following TRDF and HP TRCF at mid speed.

5.2.11 **MR speed control**: The effectiveness of MR speed (N_R) control following TRCFs was explored during the Lynx TRF programme [5] and proved successful in reducing the transient yaw rate during the RNAS Portland TRCF occurrence [14]. In this trial, N_R was controllable by the pilot using a thumb toggle on the collective, and the effectiveness of this system was explored during TRCFs in the hover.

It should be noted that the HP TRCF setting was 21° from the outset (c.f. the first trial where 26° was initially used before reverting to this value). The value used in the QinetiQ Lynx flight trial [5] was 17° but this was found to be close to the simulated hover trim value and would not therefore have represented HP TRCF.

5.3 Results

The test points carried out for high and mid speed TRDFs, and HP and LP TRCFs are shown in Table 6-12 to Table 6-15 respectively, which show paragraph cross-references where detailed time histories and pilot ratings are provided. The baseline cases are provided to enable comparisons with those of the various technologies. Overall there were 28 configuration/speed/TRF combinations flown over 57 test points (i.e. 2 TRF phases being covered on average), each of which was carried out 1.9 times on average.

Table 6-12 Mitigating technologies trial high speed TRDF test points

Configuration	TRF phase	Test pt.	No. tests	No. pilots	Paragraph
Baseline	Transient	b1	3	2	6.5.4.1
	Manoeuvre	b1	2	2	
	Landing	b1	2	2	6.5.4.1
Deployable fin	Transient	1	1	1	6.5.4.4
	Manoeuvre	1	1	1	
	Landing	1	1	1	6.5.4.4
Enlarged fin	Transient	1	2	2	6.5.4.3
	Manoeuvre	1	1	1	
	Landing	1	1	1	6.5.4.3
Drag chute	Transient	5	2	2	6.5.4.5
	Manoeuvre	5	2	2	
	Landing	5	2	2	6.5.4.5
AFCS authority	Transient	12	2	2	6.5.4.6
Warning device	Transient	18	2	2	6.5.4.7
Articulated MR	Transient	22	2	2	6.5.4.2
	Manoeuvre	22	2	2	
	Landing	22	2	2	
Warning device, Articulated MR, RC AFCS	Transient	26	2	2	
Hands on, Articulated MR, RC AFCS	Transient	27	1	1	
	Landing	27	1	1	
Hands off, Articulated MR	Transient	28	2	2	
Hands off, Articulated MR, RC AFCS	Transient	29	2	2	
Total number of tests:			38		

Table 6-13 Mitigating technologies trial mid speed TRDF test points

Configuration	TRF phase	Test pt.	No. tests	No. pilots	Paragraph
Baseline	Transient	b3	2	2	6.5.5.1
	Manoeuvre	b3	2	2	
	Landing	b3	2	2	
Drag chute	Transient	6	2	2	6.5.5.2
	Manoeuvre	6	2	2	
	Landing	6	2	2	
RC AFCS	Transient	9	2	2	6.5.5.3
	Manoeuvre	9	2	2	
	Landing	9	2	2	
Delayed reaction	Transient	20	2	2	6.5.5.4
Delayed reaction, Enlarged fin	Transient	21	2	2	6.5.5.5
Articulated MR	Transient	24	2	2	6.5.5.6
	Manoeuvre	24	2	2	
	Landing	24	2	2	
Articulated MR, RC AFCS	Transient	25	2	2	6.5.5.7
Articulated rotor, Delayed reaction	Transient	30	2	2	6.5.5.8
Articulated rotor, Delayed reaction, Enlarged fin	Transient	31	2	2	6.5.5.9
Total number of tests:			34		

Table 6-14 Mitigating technologies trial HP TRCF test points

Speed	Configuration	TRF phase	Test pt.	No. tests	No. pilots	Paragraph
High	Baseline	Transient	b2	2	2	
		Manoeuvre	b2	2	2	
		Landing	b2	2	2	
	Deployable fin	Transient	2	2	2	
		Manoeuvre	2	2	2	
		Landing	2	1	1	
	Drag chute	Transient	7	3	2	
		Manoeuvre	7	2	2	
		Landing	7	3	2	
Mid	Baseline	Transient	b4	1	1	
Hover	Baseline	Transient	b6	2	2	6.5.6.1
	N_R control	Transient	14	3	2	6.5.6.2
Total number of tests:				25		

Table 6-15 Mitigating technologies trial LP TRCF test points

Speed	Configuration	TRF phase	Test pt.	No. tests	No. pilots	Paragraph
High	Baseline	Transient	b7	2	2	
		Manoeuvre	b7	2	2	
		Landing	b7	2	2	
	Drag chute	Transient	32	2	2	
		Manoeuvre	32	2	2	
		Landing	32	2	2	
Total number of tests:				12		

5.4 **TRDF at high speed**

5.4.1 **Baseline configuration**: Figure 6-23 shows time histories of the transient phase following a TRDF at high speed for the baseline configuration and is comparable to that shown in Figure 6-3 for the first trial. All transient phase plots show a timescale in seconds where zero is the point of failure. The pilot initiated the recovery after a PIT of 1.92 seconds by reducing the collective to zero and shutting down both engines. The aircraft yawed to starboard developing a port sideslip of 50° before the pilot initiated recovery action. The yaw transient was accompanied by a strong roll to starboard of more than 90° in 3 seconds. Note that the pilot had not applied much lateral cyclic to compensate. As was found in the first trial, this combination of roll and yaw exposed the MR to a very high angle of aerodynamic incidence and, with the collective reduced to zero, the inevitable result is that N_R exceeded 150%. The pilot increased collective pitch between 3 and 5 seconds in an attempt to control the overspeeding MR. The aircraft decelerated rapidly to about 70 kn in the first few seconds after the failure, as the large sideslip angle developed and the MR thrust, increased by the MR speed transient, opposed the forward motion. The aircraft climbed initially as a result of the increased thrust and then descended, settling into full autorotation at about 3000 ft/min at 90 kn after about 20 seconds. A HQR of 9 (Level 4; high risk of losing control) and FRR G (recovery marginal) were returned. The simulation was not able to model the structural damage that would have been caused by such large excursions in MR speed and sideslip, but it is likely that major damage would have been incurred. The same caveats on simulation model fidelity that were made for the first trial apply (see 6.4.4). In summary, it is unlikely that the MR would have generated such high levels of thrust during the MR spin-up, and the increased drag would certainly have resulted in much reduced transients.

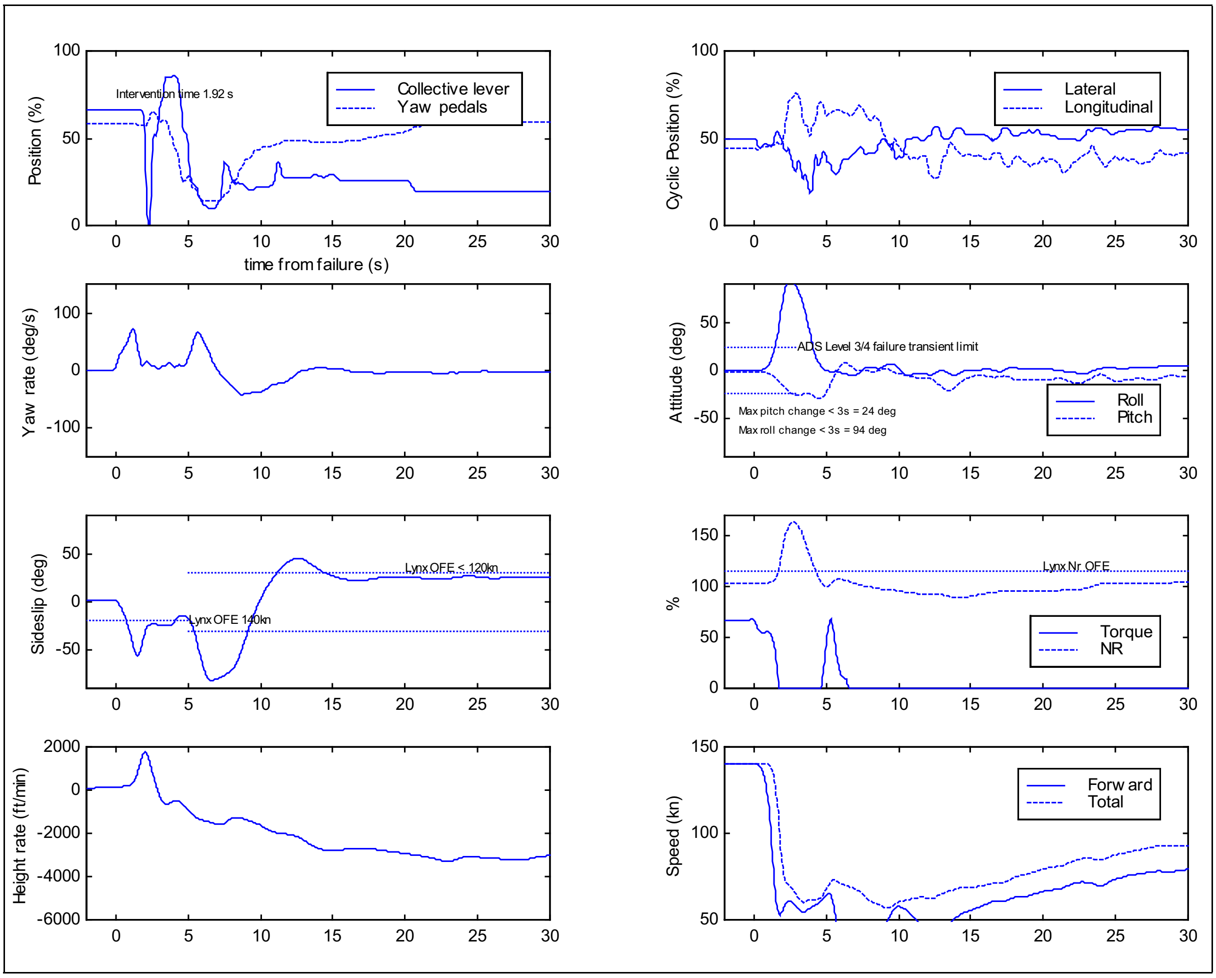

Figure 6-23 Time histories for transient phase of TRDF at high speed (P3, baseline)

Figure 6-24 shows data for the landing phase of a similar TRDF. All plots for the landing phase show a timescale in seconds with zero at the point of touchdown. In addition, for the landing phase of all cases, and for the hover cases, the lateral velocity time history is presented alongside that of sideslip. The aircraft touched down at about 40 kn with a very low rate of descent (<3 ft s-1). However, with more than 20° of sideslip angle, the pilot had failed to cancel the lateral drift and the aircraft would almost certainly have rolled over on contact with the ground. The pilot returned a Level 4 rating of 10G.

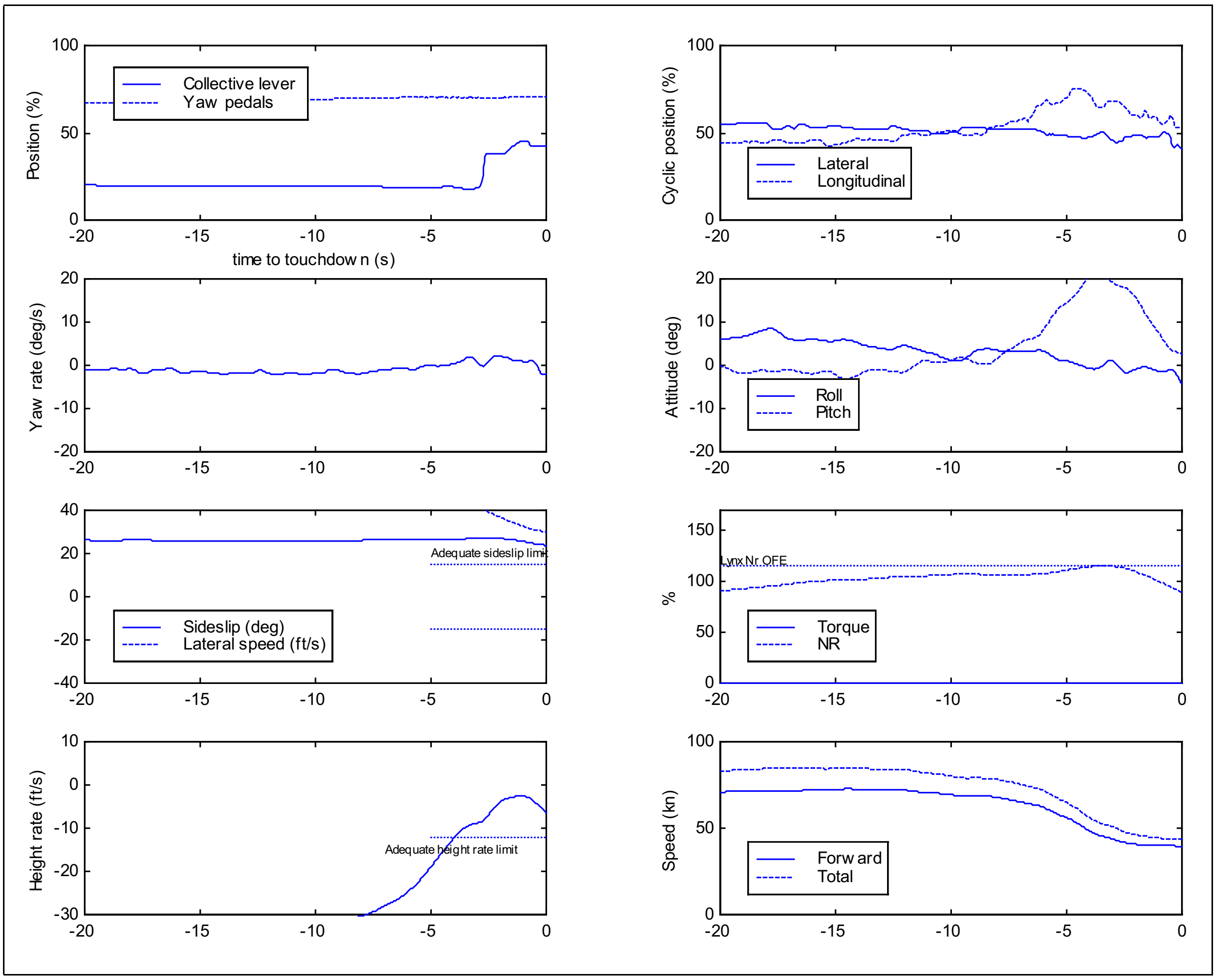

Figure 6-24 Time histories for landing phase of TRDF at high speed (P3, baseline)

5.4.2 **Articulated MR**: Figure 6-25 shows results for the model with the articulated MR system. This case was examined to evaluate potential differences between aircraft like the Lynx, with stiff MRs, and aircraft with more conventional MRs, but in the same weight category, like the S-76 or Dauphin. Compared to Figure 6-23, there appears to be increased cyclic activity but reduced collective activity (due to the less responsive rotor) and the rotor speed remains high for longer (possibly impacting the height rate). However, the areas where significant differences might have been expected were the transient pitch and roll responses during the failure, but the differences were not significant either in the transient phase as shown or in the landing phase; Level 4 ratings of 9H and 9G were returned respectively.

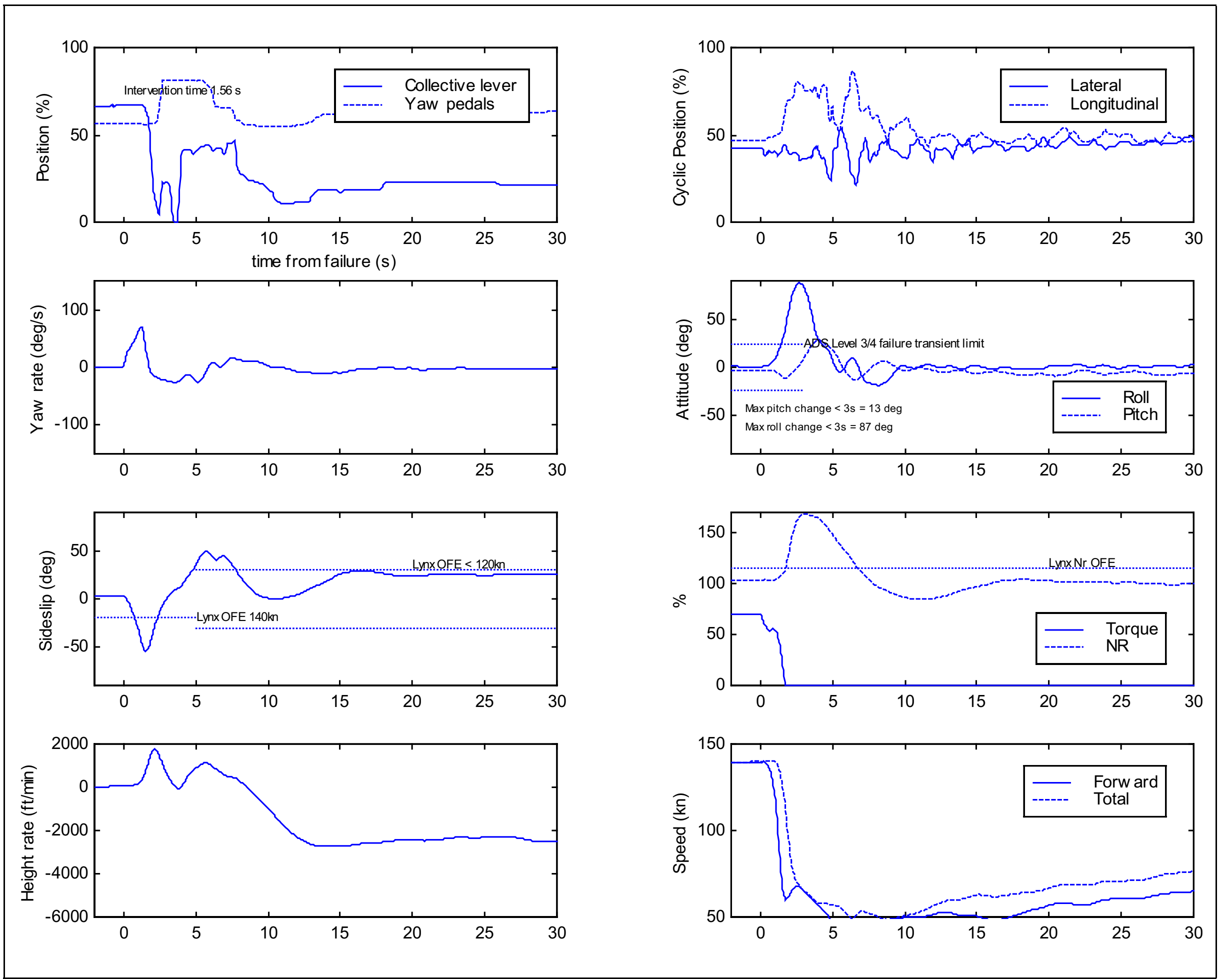

Figure 6-25 Time histories for transient phase of TRDF at high speed (P3, articulated MR)

5.4.3 **Enlarged fin**: An example of the transient phase results for the enlarged fin is shown in Figure 6-26. Both pilots delayed initial recovery action until after 2 seconds and neither found it necessary to shut down the engines in order to re-establish a trim condition. The reduced transients conferred by this change were quite dramatic. The pilot returned a HQR of 4 (good Level 2) and a FRR of C (transients not objectionable, moderate urgency). Sideslip and roll angle transients within 3 seconds were about 20° and 25° respectively. MR speed transients were only a few percent and the pilot had essentially re-established control within 10 seconds, with a loss of airspeed of about 20 kn.

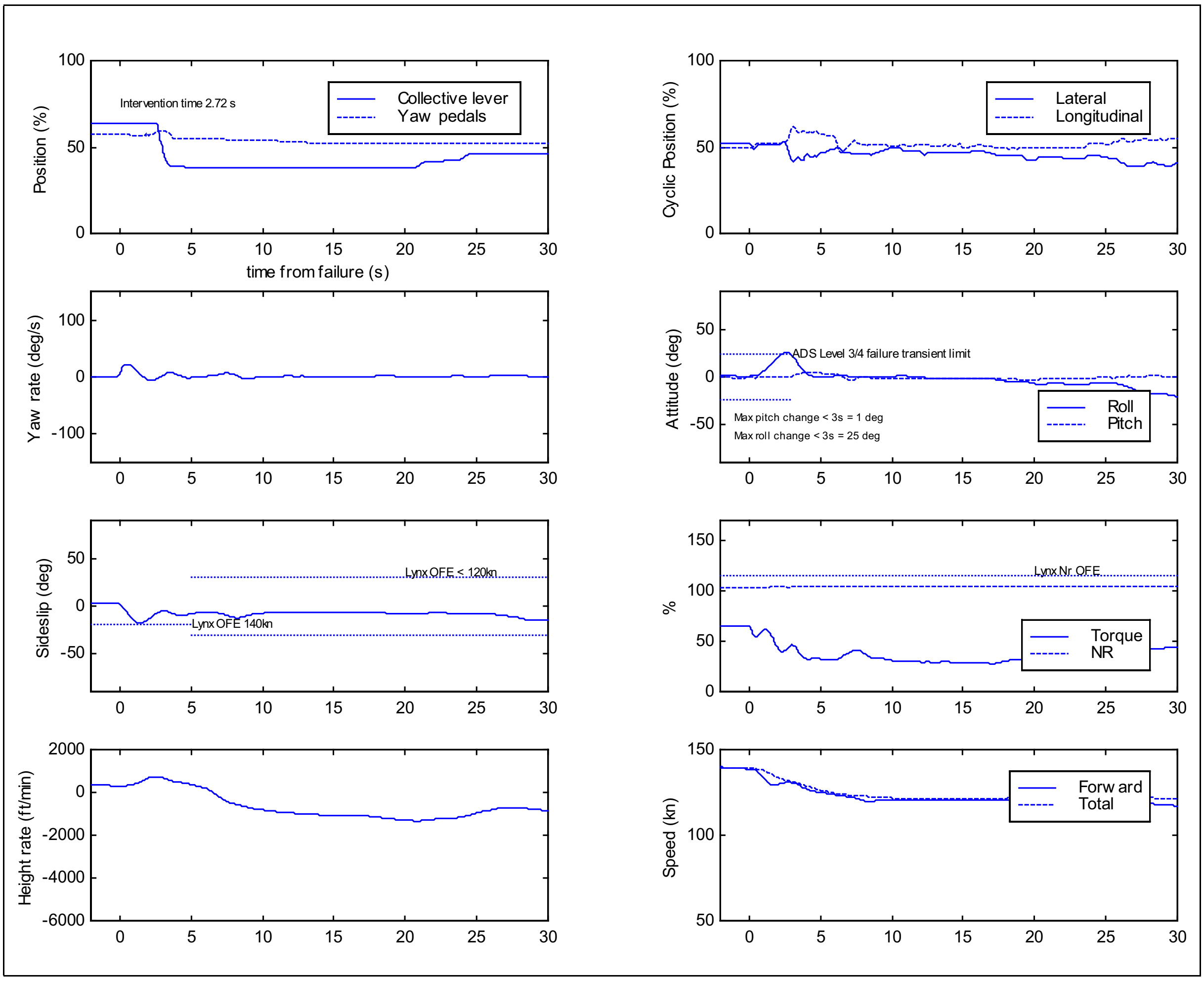

Figure 6-26 Time histories for transient phase of TRDF at high speed (P2, enlarged fin)

Figure 6-27 shows the landing phase for the enlarged fin configuration. The pilot had shut the engines down by this stage and landed at about 20 kn with 10 ft s^{-1} vertical and lateral velocities; the MR speed had decayed to about 80% at this stage. A Level 2 rating of 5F was awarded. Although seen as beneficial in this case, the effect on inherent sideslip during autorotation could become detrimental if the fin area is too large and provides an excessive residual anti-torque moment.

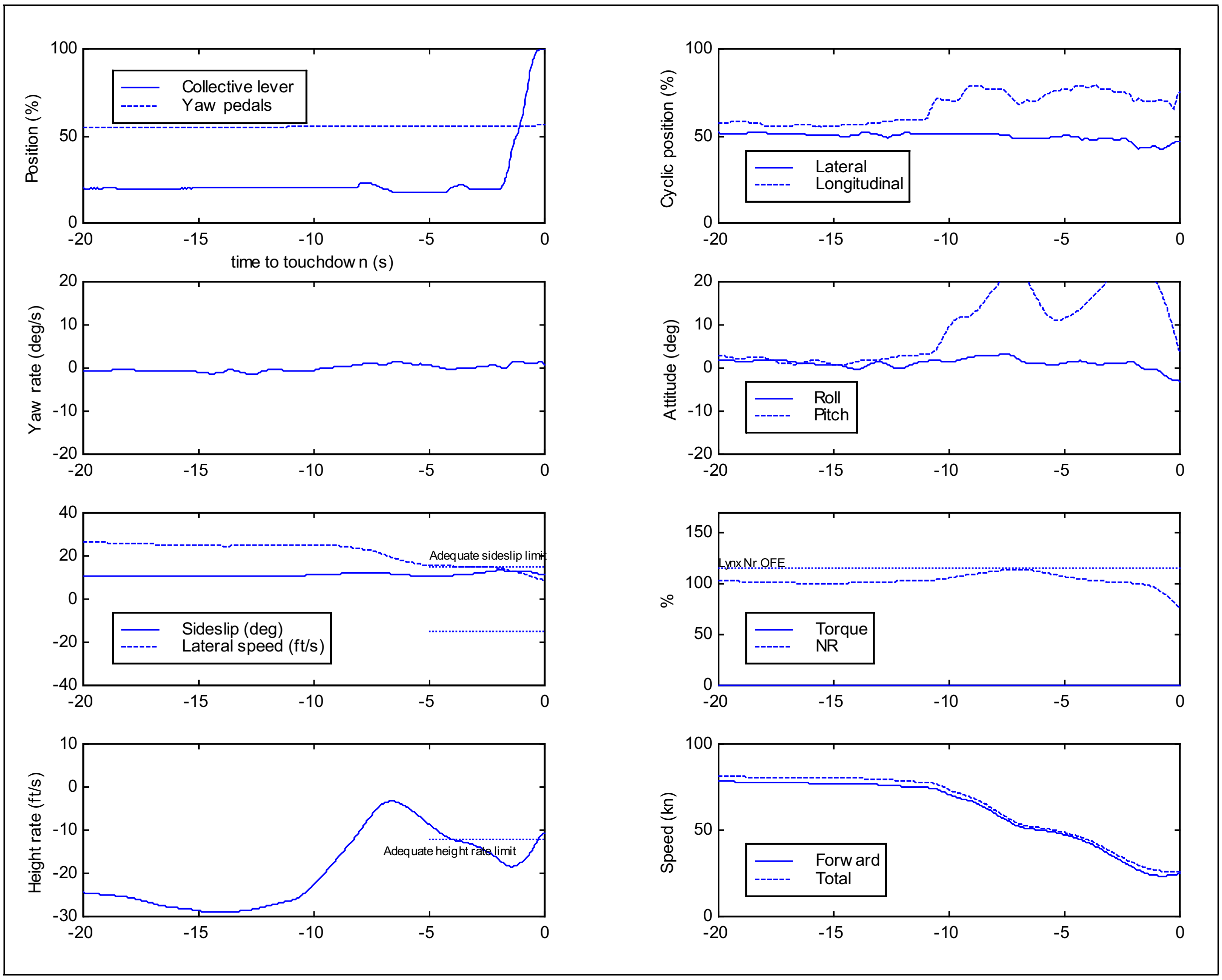

Figure 6-27 Time histories for landing phase of TRDF at high speed (P3, enlarged fin)

5.4.4 **Deployable fin**: The results for this case are shown in Figure 6-28, with the pilot initiating recovery at 2 seconds. Since the sideslip and roll motions built up to their peak within 2 seconds, the deployment delay of 2 seconds meant that this device made no contribution to reducing the initial transients. The pilots were asked to rate the effectiveness of the device after deployment (in this case a Level 2 rating of 6D). In hindsight, this approach prevented useful comparison with other cases apart from the drag chute where the same approach was taken; the initial transients were clearly as severe as with the baseline configuration, which attracted much worse ratings.

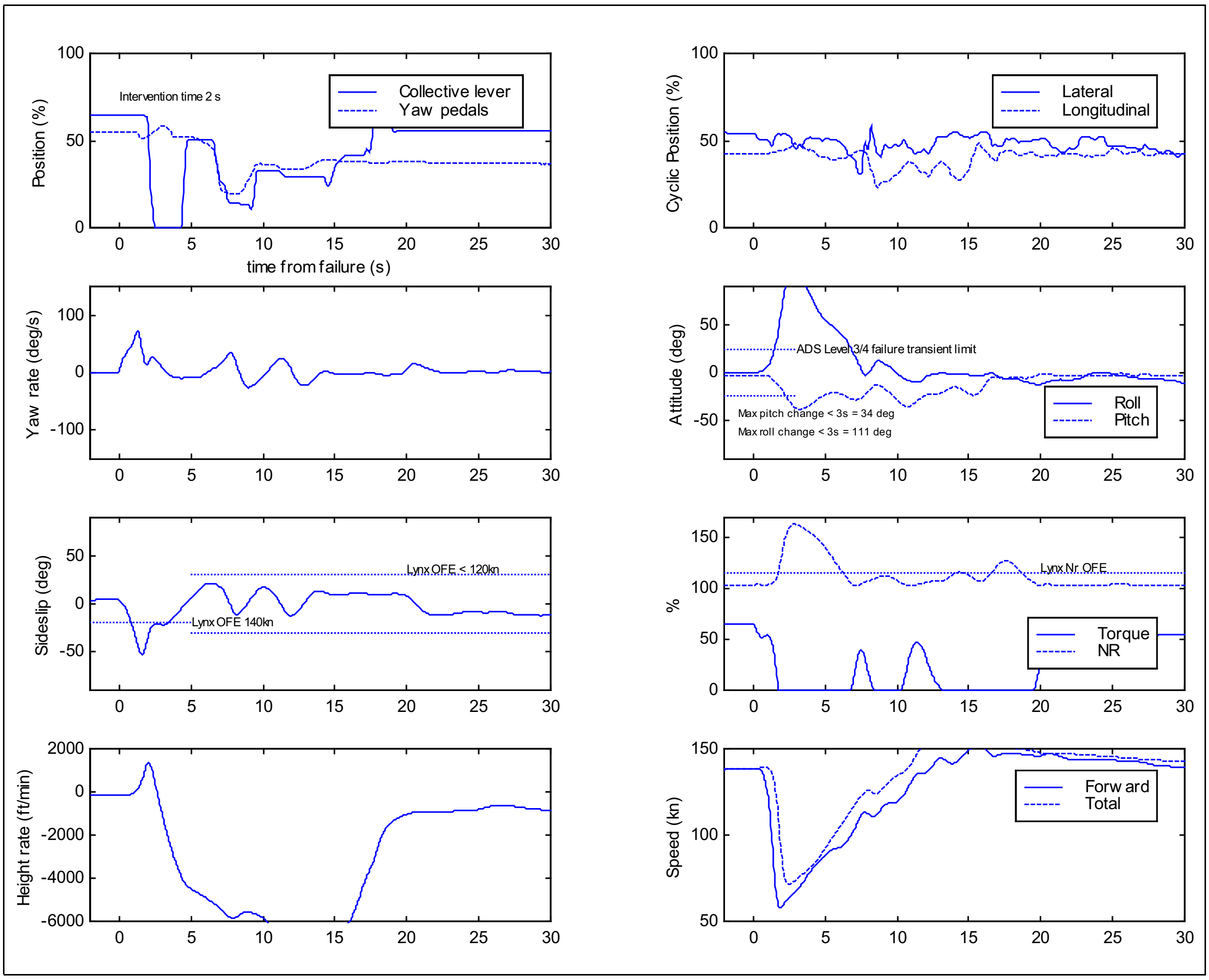

Figure 6-28 Time histories for transient phase of TRDF at high speed (P2, deployable fin)

Figure 6-29 shows the last 20 seconds before touchdown at about 60 kn. The aircraft was just outside the vertical velocity limits at touchdown and had more than 20 ft s^{-1} lateral velocity. The pilot returned a Level 2 rating of 6E, presumably unaware of the velocity limit exceedances.

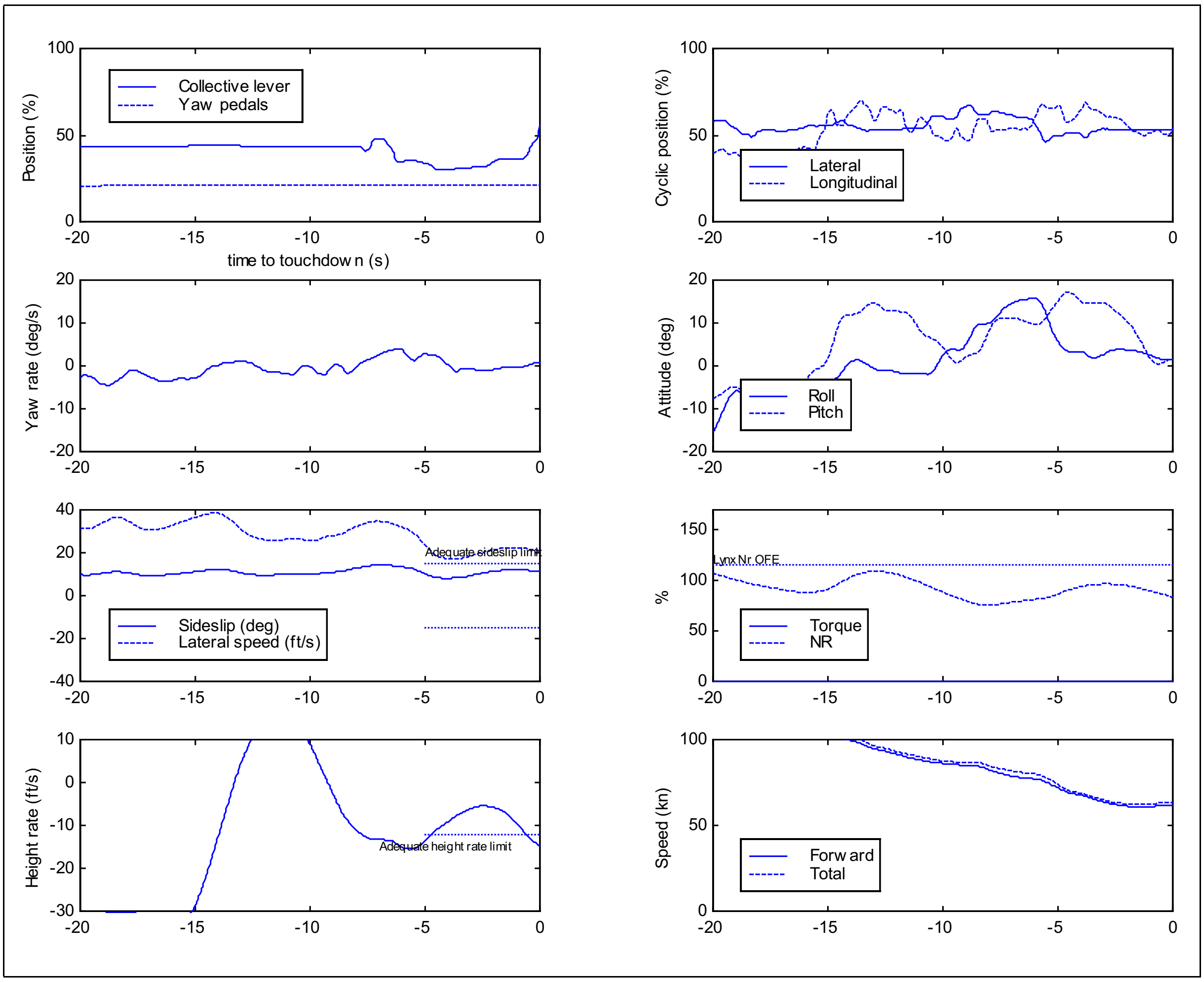

Figure 6-29 Time histories for landing phase of TRDF at high speed (P2, deployable fin)

5.4.5 **Drag chute**: The results for the drag chute are given in Figure 6-30, with the pilot initiating recovery in 1.8 seconds. The Level 2 rating of 5D for this case was attributed to the ability to recover following deployment, hence cannot be compared with other cases except for the deployable fin. The failure transients reflect that manual deployment was after the PIT. A sharp jolt was experienced by the crew on deployment. Sideslip and roll built up to 60° and 80° respectively within the first few seconds, followed by the familiar MR speed excursion to 150%.

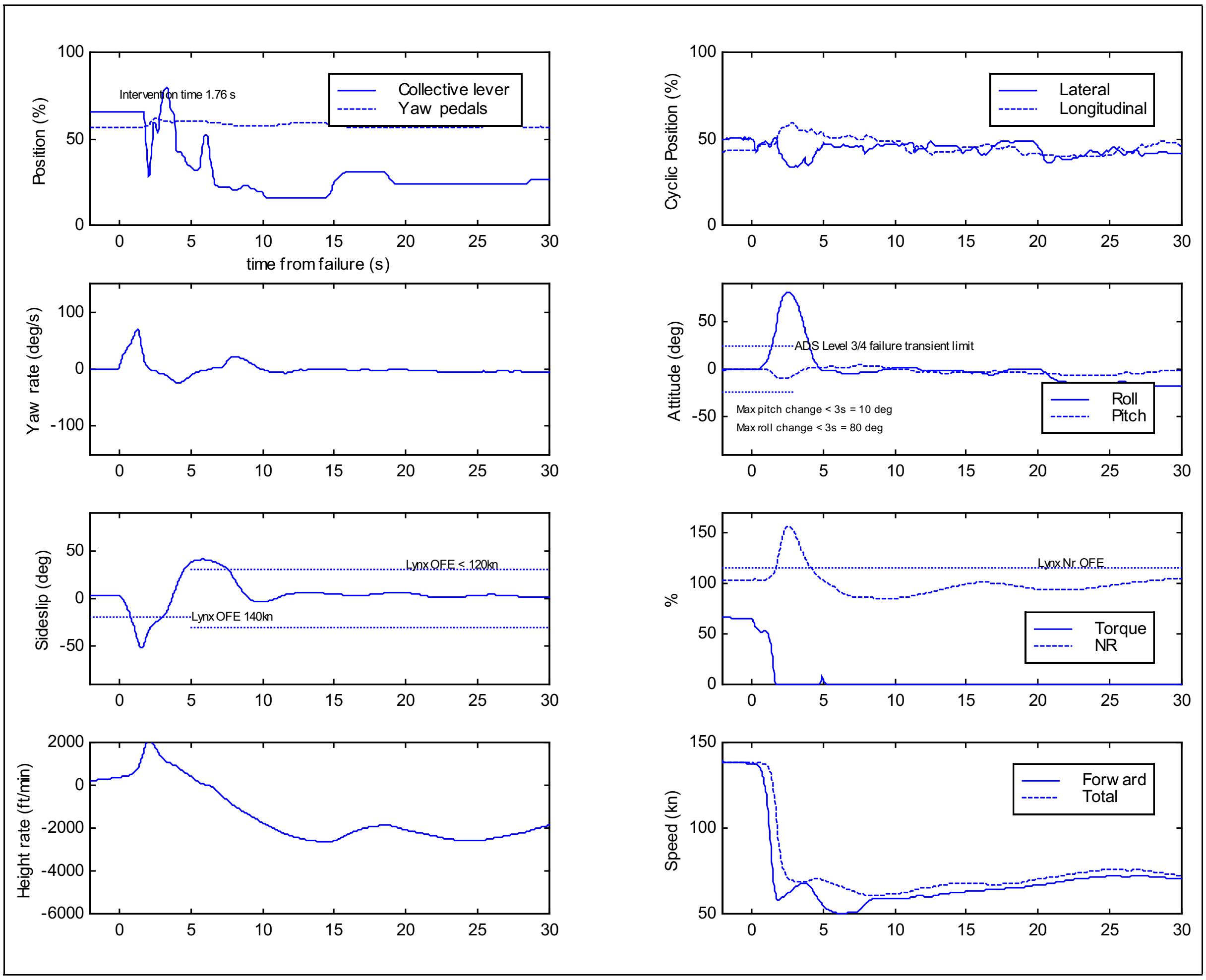

Figure 6-30 Time histories for transient phase of TRDF at high speed (P3, drag chute)

Figure 6-31 shows that the pilot landed with the deployed drag chute at about 30 kn, with vertical and horizontal velocities of 18 ft s^{-1} and 6 ft s^{-1} respectively, returning a Level 2 rating of 5D. The aircraft was pitched up by about 15° at touchdown. Depending on the nature of the ground surface, this high pitch attitude (resultant tail impact) may serve to align the aircraft around onto the direction of flight and increase the survival chances.

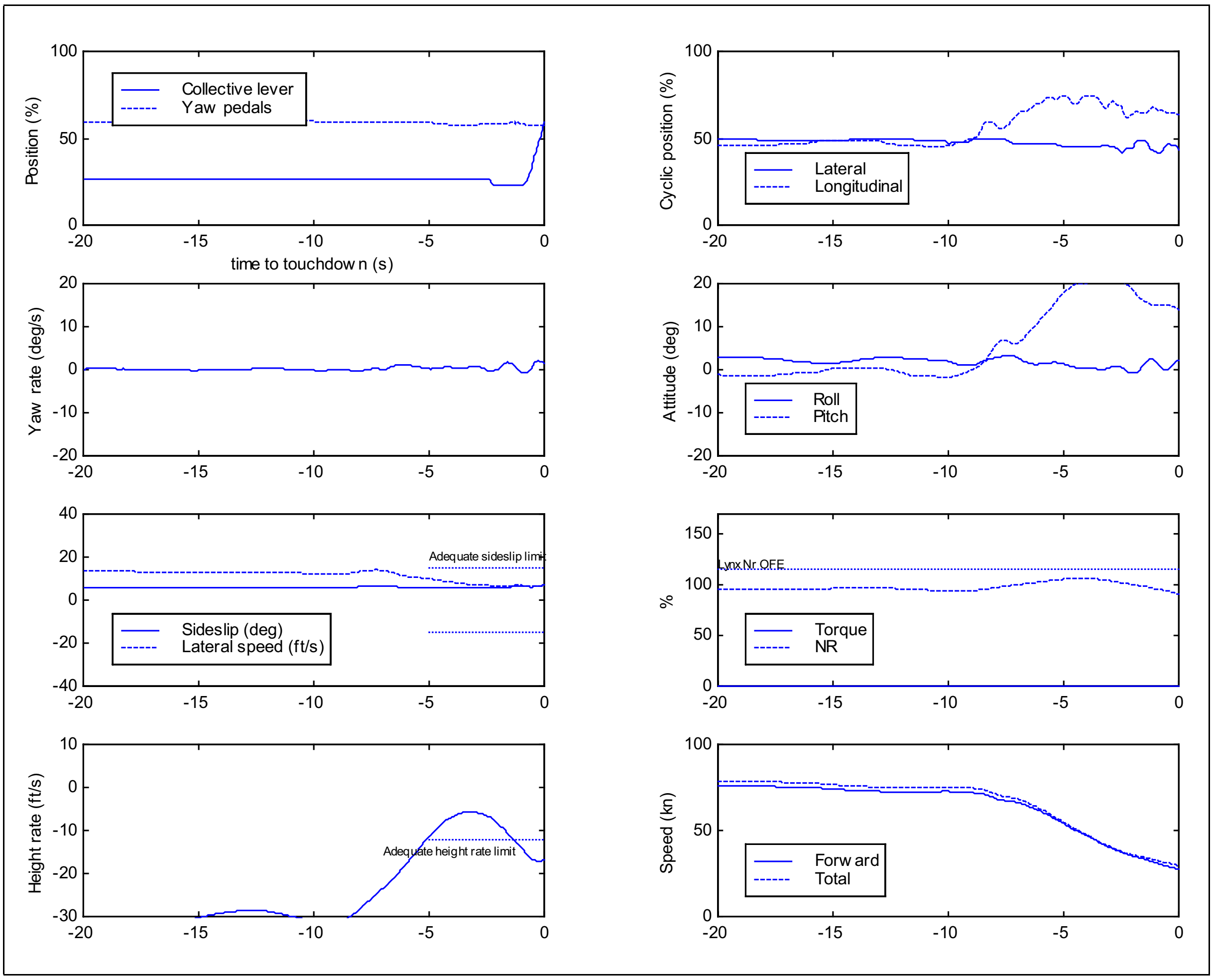

Figure 6-31 Time histories for landing phase of TRDF at high speed (P3, drag chute)

5.4.6 **AFCS authority**: The increased (to 20%) pitch/roll AFCS authority transient results are shown in Figure 6-32. The pilot initiated recovery at 2.08 seconds, reducing the collective to zero. The AFCS had no effect on sideslip of course, hence the usual build-up to about 60° within the first 2 seconds. The AFCS did hold the roll attitude transients, however, in this case to a peak of 41° in 3 seconds. MR speed rose to the OFE limit of 116% but no higher. The transient phase was awarded a Level 2 rating of 5D.

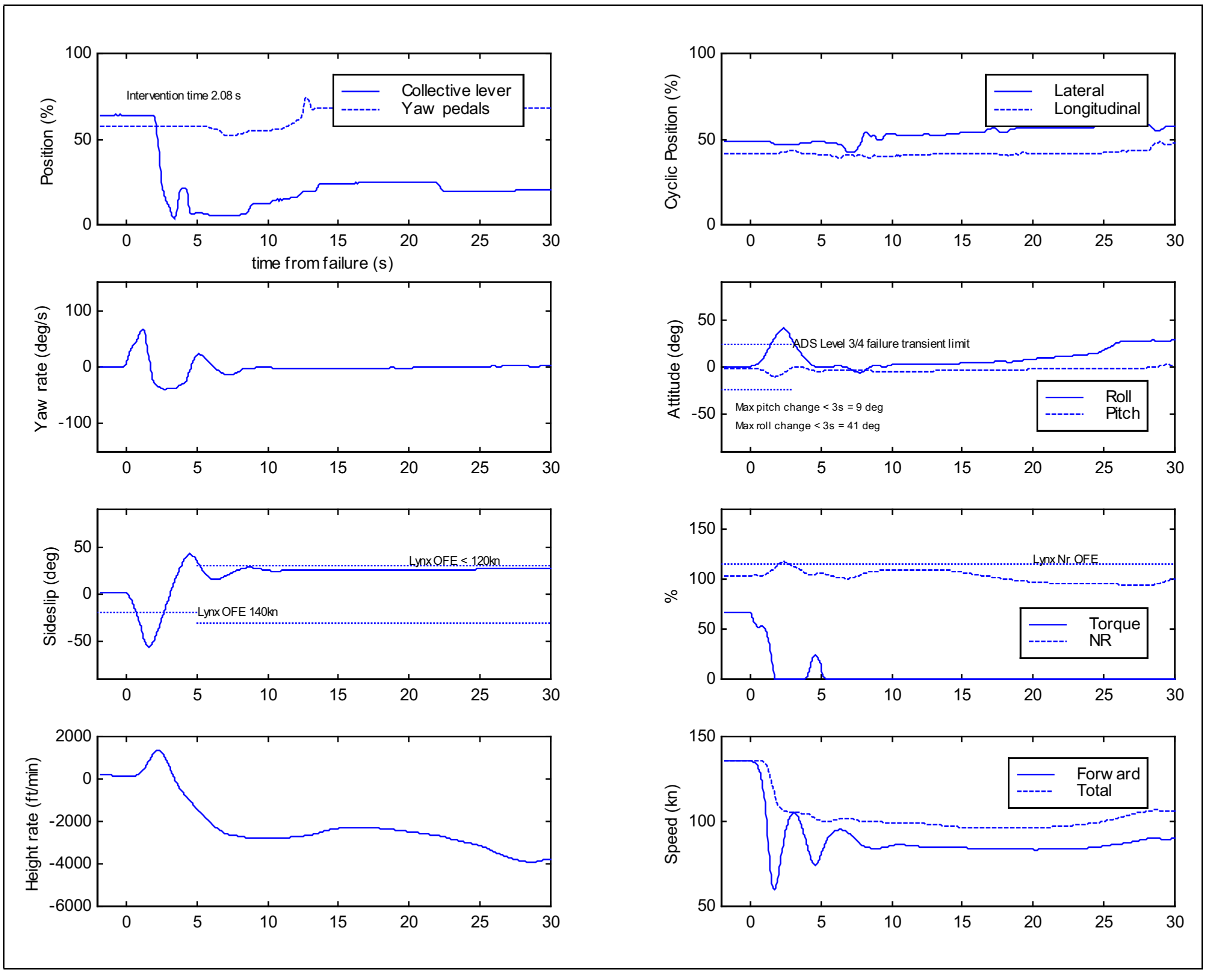

Figure 6-32 Time histories for transient phase of TRDF at high speed (P2, AFCS authority)

5.4.7 **Warning device**: The reduced PIT transient results for the baseline configuration are shown in Figure 6-33, simulating a pilot fully active on the controls, responding quickly to a warning device. The measured PITs for both pilots were actually about 1.25 seconds. With the yaw rate building to about 60° s^{-1} within 1 second, neither pilot could do much to subdue the associated sideslip build-up; so again we see sideslip peaking at more than 50° within 2 seconds. Roll attitude was held to lower transients by the pilot however, with a peak of 46° within 3 seconds. Reduced roll transients and use of collective by the pilot reduced MR speed excursions to about 125% in this case. The pilot of the case shown returned a Level 2 rating of 6E (6F for P3). Rapid reaction by the pilot, cued by a warning/annunciation device clearly has benefits.

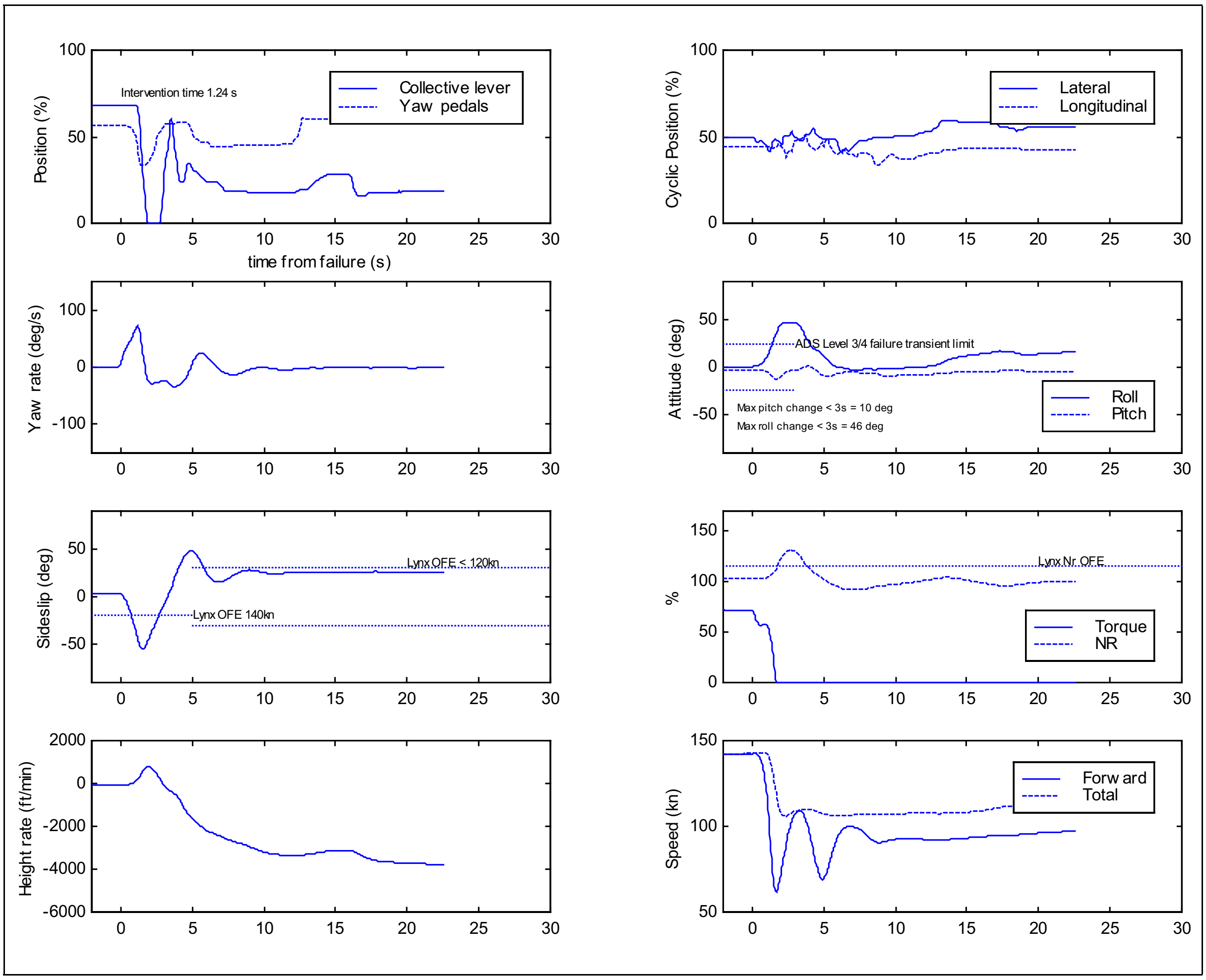

Figure 6-33 Time histories for transient phase of TRDF at high speed (P2, warning device)

5.4.8 **Attitude transients**: The attitude transients within 3 seconds of TRDF for the various configurations are collected together in Figure 6-34. It can be seen that the baseline and articulated MR configurations, and the configurations with deployable safety devices all experience large pitch, roll and yaw attitude excursions following the failure. The increased authority attitude stabilisation reduces the pitch and roll transients by more than 60%; this effect also resulted from simulated use of a warning device. The enlarged fin configuration is shown along with the MYR 2 and MYR 3 configurations from the first trial data for comparison. The powerful effect of increased fin effectiveness is shown by the data, with the yaw transient for the second trial enlarged fin configuration reduced to about 30% of the transient excursion experienced with that of the baseline. The heading and roll transient data for this increased fin configuration lie on the Level 3/4 boundary (24° attitude change within 3 s, shown as the dashed line) for failure handling qualities in near-Earth flight conditions.

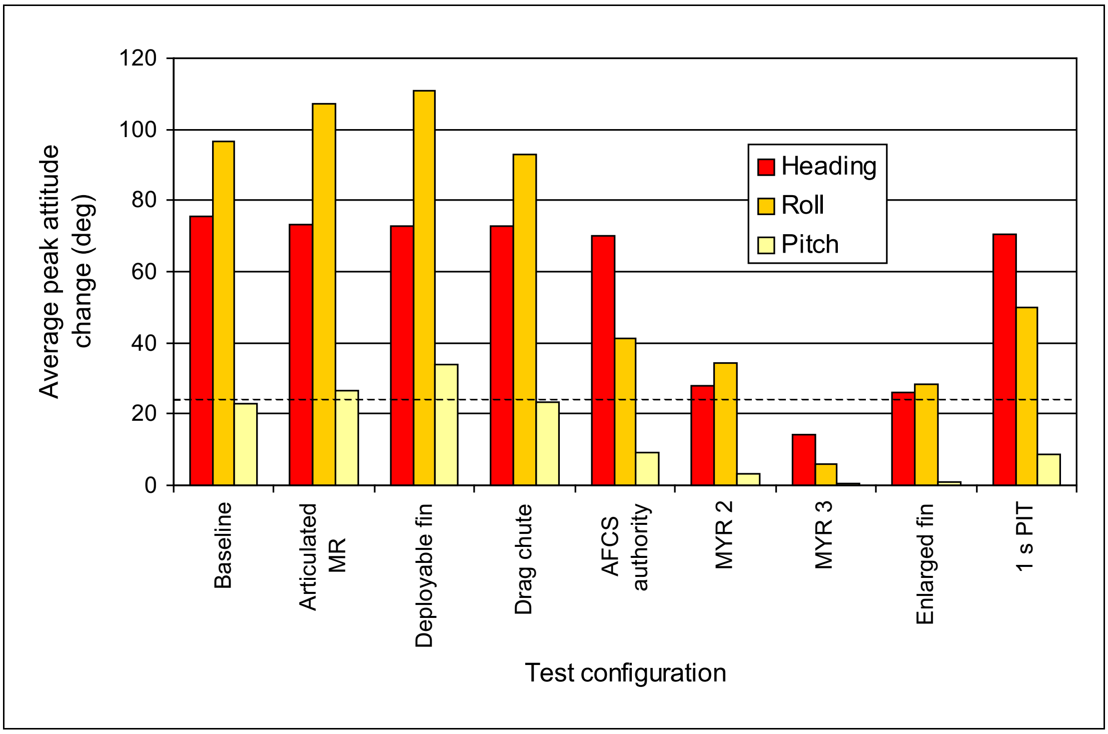

Figure 6-34 Transient attitudes for TRDF at high speed

5.4.9 **Pilot ratings**: The range of pilot ratings are shown in Figure 6-35 and demonstrates the point that to achieve Level 2 handling qualities requires increased fin size; increased attitude stabilisation also helps. Note that for the drag chute and deployable fin cases, the pilot ratings were awarded on a different basis and can therefore be meaningfully compared only with each other.

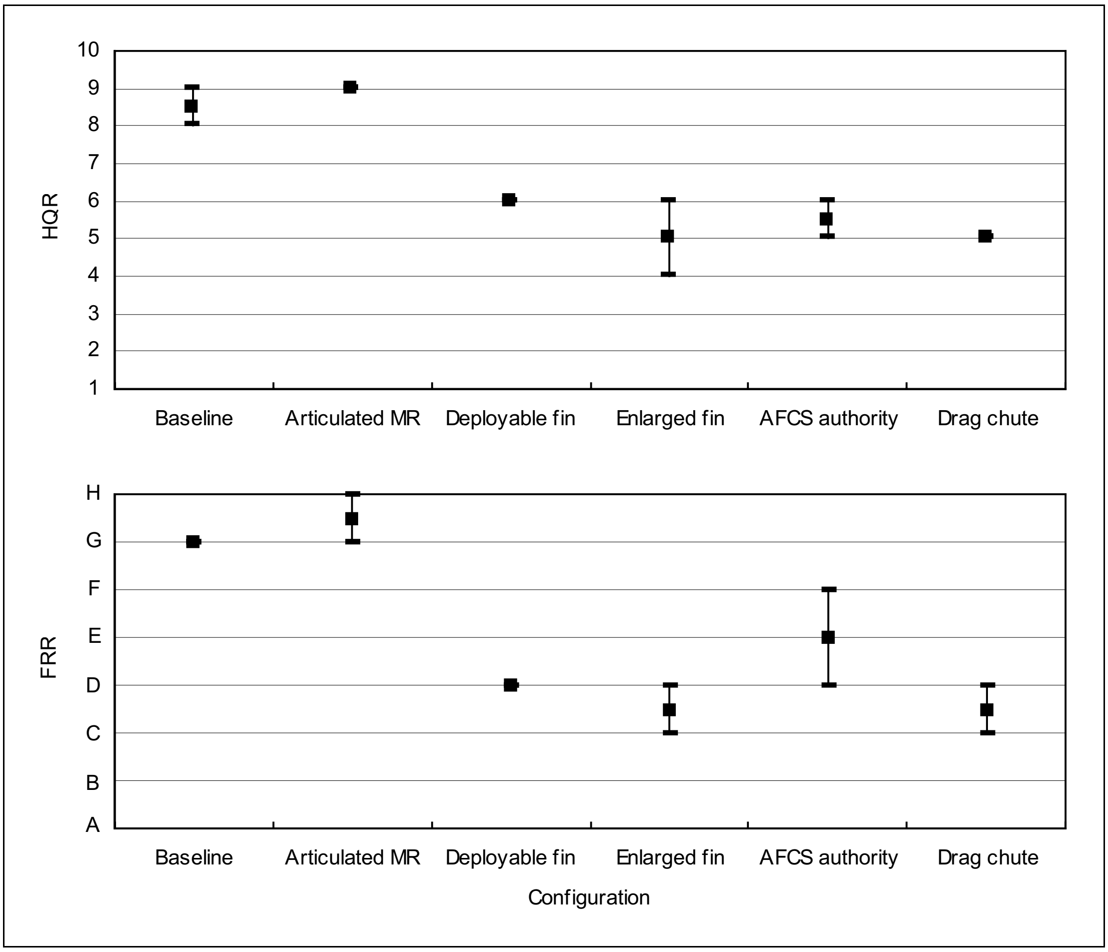

Figure 6-35 Pilot ratings for transient phase of TRDF at high speed

Figure 6-36 shows the HQRs and FRRs for various PITs. The ratings show clearly that decreasing the PIT towards 1 second has a significant effect on survivability, improving the situation from borderline Level 3/4 to borderline Level 2/3.

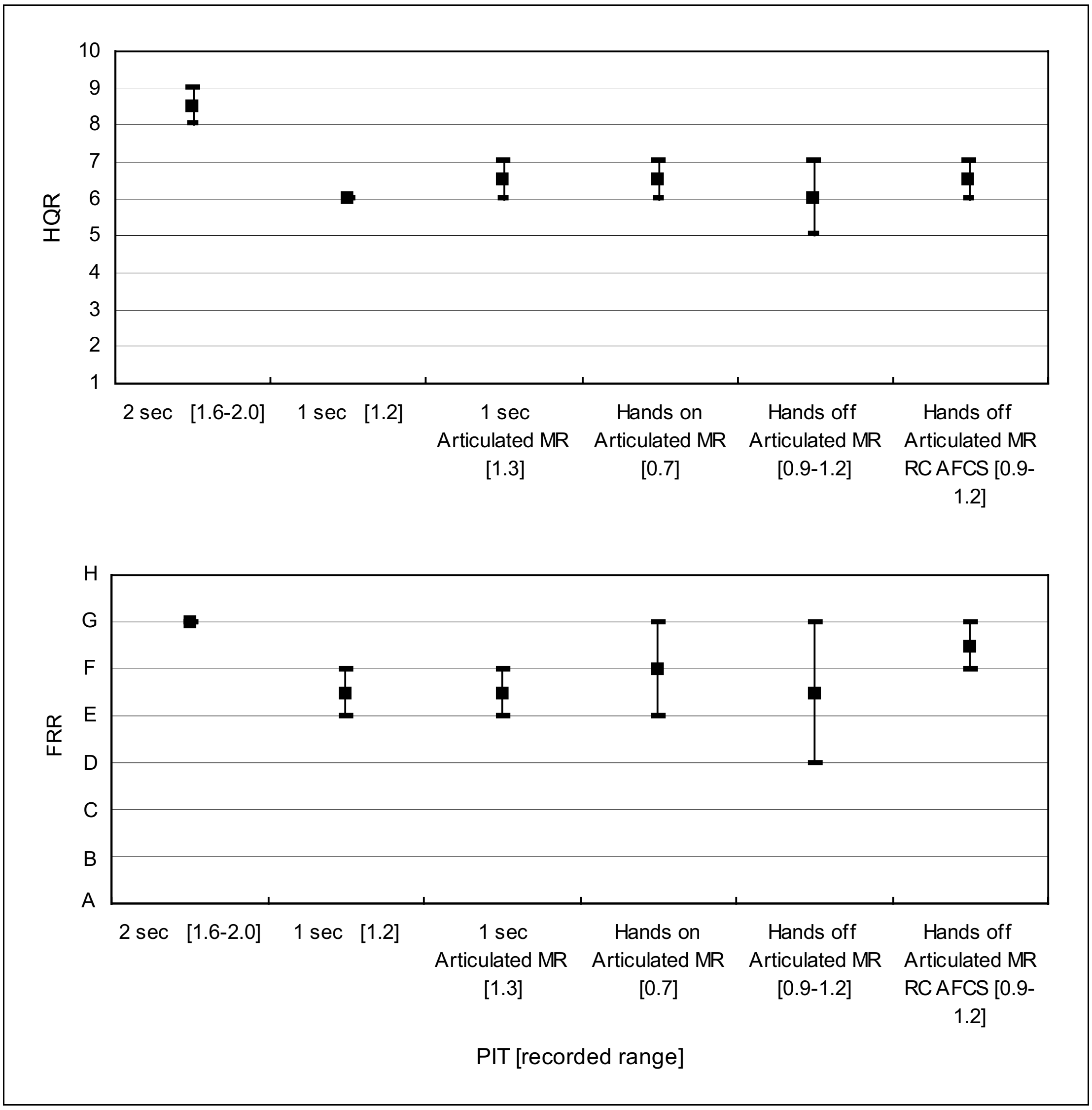

Figure 6-36 Pilot ratings for various PITs for transient phase of TRDF at high speed

5.5 TRDFs at mid speed

Transient responses following TRDF at mid speed are not expected to be as severe as those at high speed. The MR torque is close to minimum for straight and level flight at only about 50% of maximum. However, the stabilising effect of the vertical fin is reduced compared with the high speed case, so large sideslip angle transients should still be expected. A wide range of mid speed cases were chosen for examination in this trial to establish how variations from the baseline configuration fared in this potentially more benign flight condition. The results are shown in the following paragraphs.

5.5.1 **Baseline configuration**: Figure 6-37 illustrates the results with P3 intervening at 2.2 seconds. Sideslip built up to greater than 60° before the pilot reduced collective to about 5%; in this case the pilot did not shut the engines down until about 7 seconds into the failure. Roll and pitch angle transients remained within the Level 3/4 boundaries. MR speed transients during the failure were very small, and only rose towards the OFE during recovery to full autorotation at about 14 seconds. Speed reduced to about 60 kn during the transient. The pilot returned a Level 2 rating of 5F.

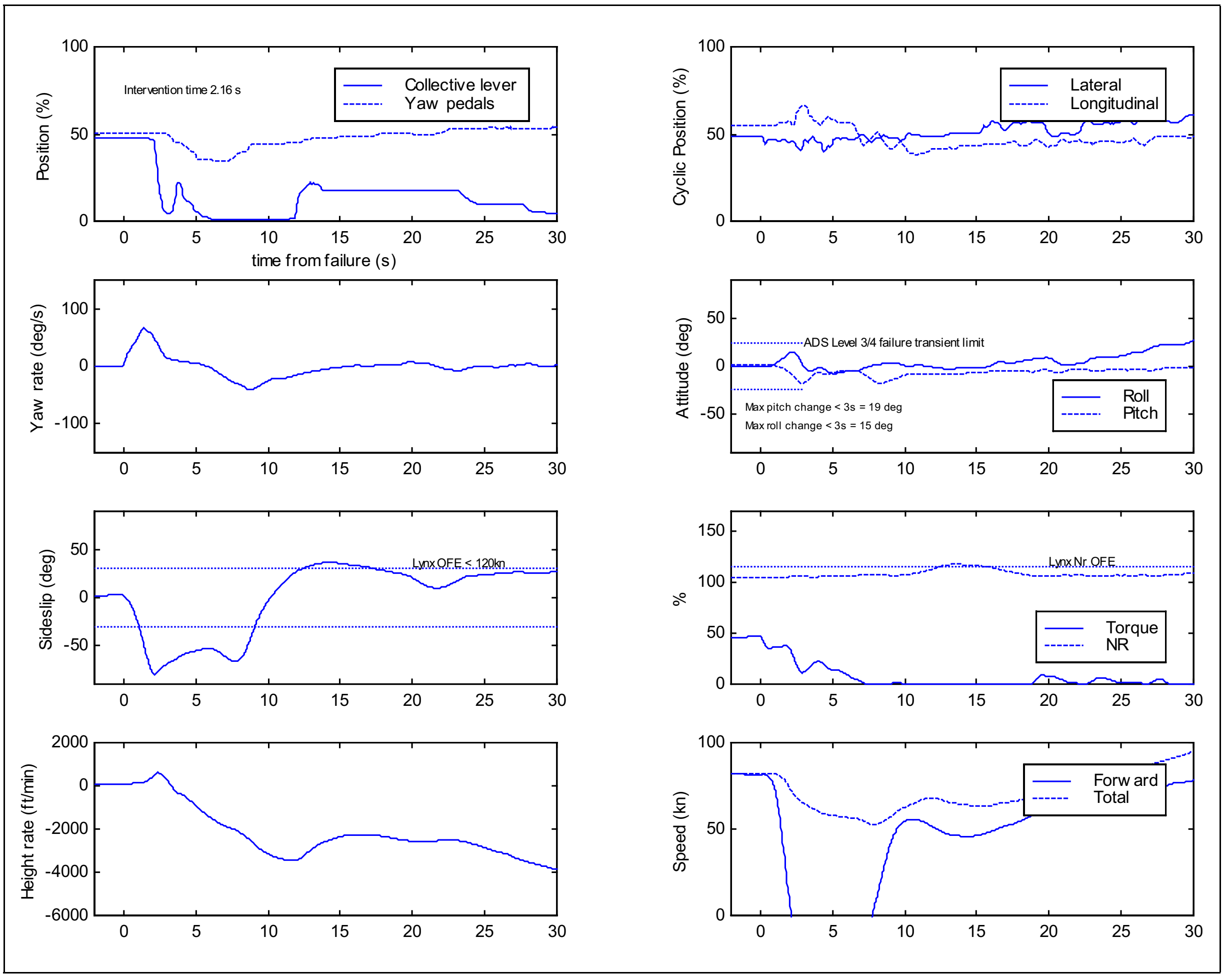

Figure 6-37 Time histories for transient phase of TRDF at mid speed (P3, baseline)

5.5.2 **Drag chute**: As in the high speed case, the drag chute had little effect on the initial transient until deployment after the baseline PIT as shown in Figure 6-38. The sideslip exceeded 60°, and the pilot returned a Level 2 rating of 6F. As with the high speed case, this rating cannot be compared with other cases apart from the deployable fin.

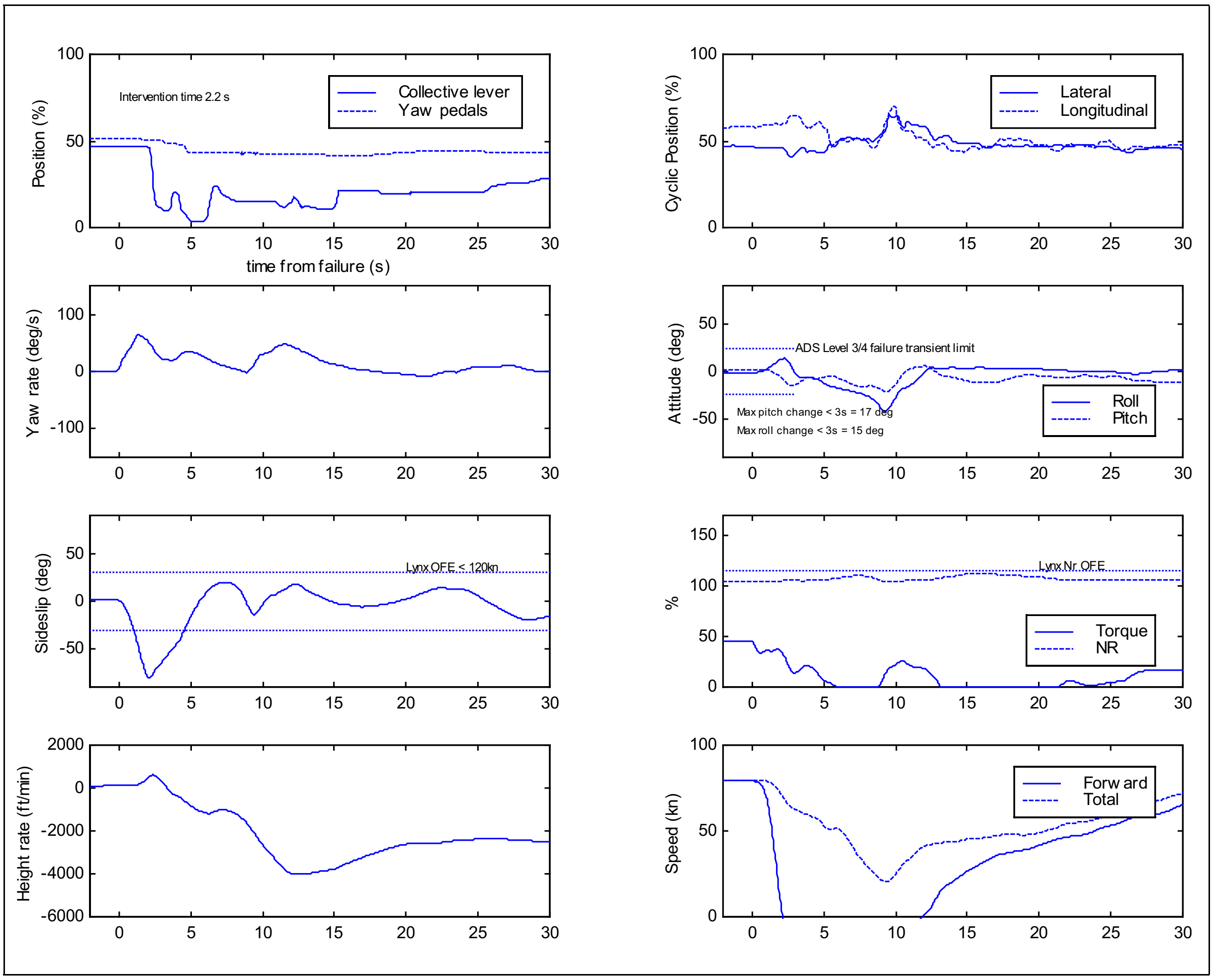

Figure 6-38 Time histories for transient phase of TRDF at mid speed (P3, drag chute)

5.5.3 **RC AFCS**: Figure 6-39 illustrates the responses to a TRDF with the ACAH control function disabled. The pilot reacts at 2.16 seconds, holding the sideslip to about 80° in this case. The roll attitude increases to about 16° in 3 seconds which is followed by a MR speed transient of over 120%. The pilot returned a Level 2 rating of 6E, slightly worse than for the baseline, for which the responses were very similar. The benefit of ACAH, as featured in the baseline configuration is not particularly apparent at this speed, especially when associated with only 10% AFCS authority.

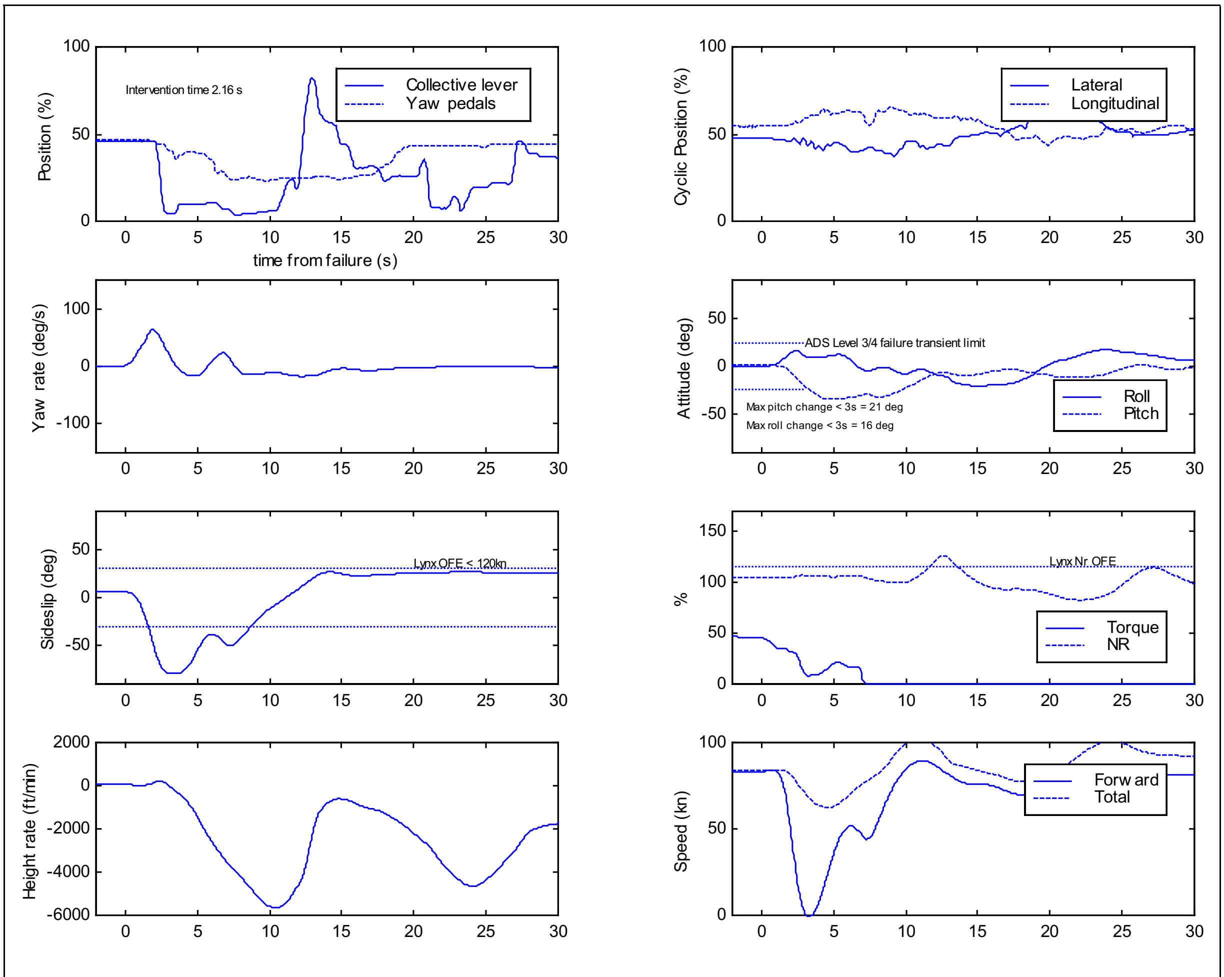

Figure 6-39 Time histories for transient phase of TRDF at mid speed (P2, RC AFCS)

5.5.4 **Delayed reaction**: Simulating the delayed reaction time of an inattentive pilot, Figure 6-40 shows results for a 4 second PIT. The pilot returned a Level 3 rating of 8G. Transient sideslip, roll and pitch angles were significant. Even at mid speed, the PIT is critical to a successful recovery strategy.

Figure 6-40 Time histories for transient phase of TRDF at mid speed (P3, delayed reaction)

5.5.5 **Enlarged fin and delayed reaction**: The powerful effect of the enlarged fin on reducing the sideslip and attitude transients is shown in Figure 6-41. The alleviation was less than at the high speed condition, where the vertical stabiliser carries most of the requirement for balancing the MR torque. Sideslip and roll angle both exceeded 50° during the failure transient; the pilot had re-trimmed the aircraft in autorotation at 2000 ft/min at an airspeed of about 60 kn 15 seconds after the failure and returned a Level 2 rating of 5G.

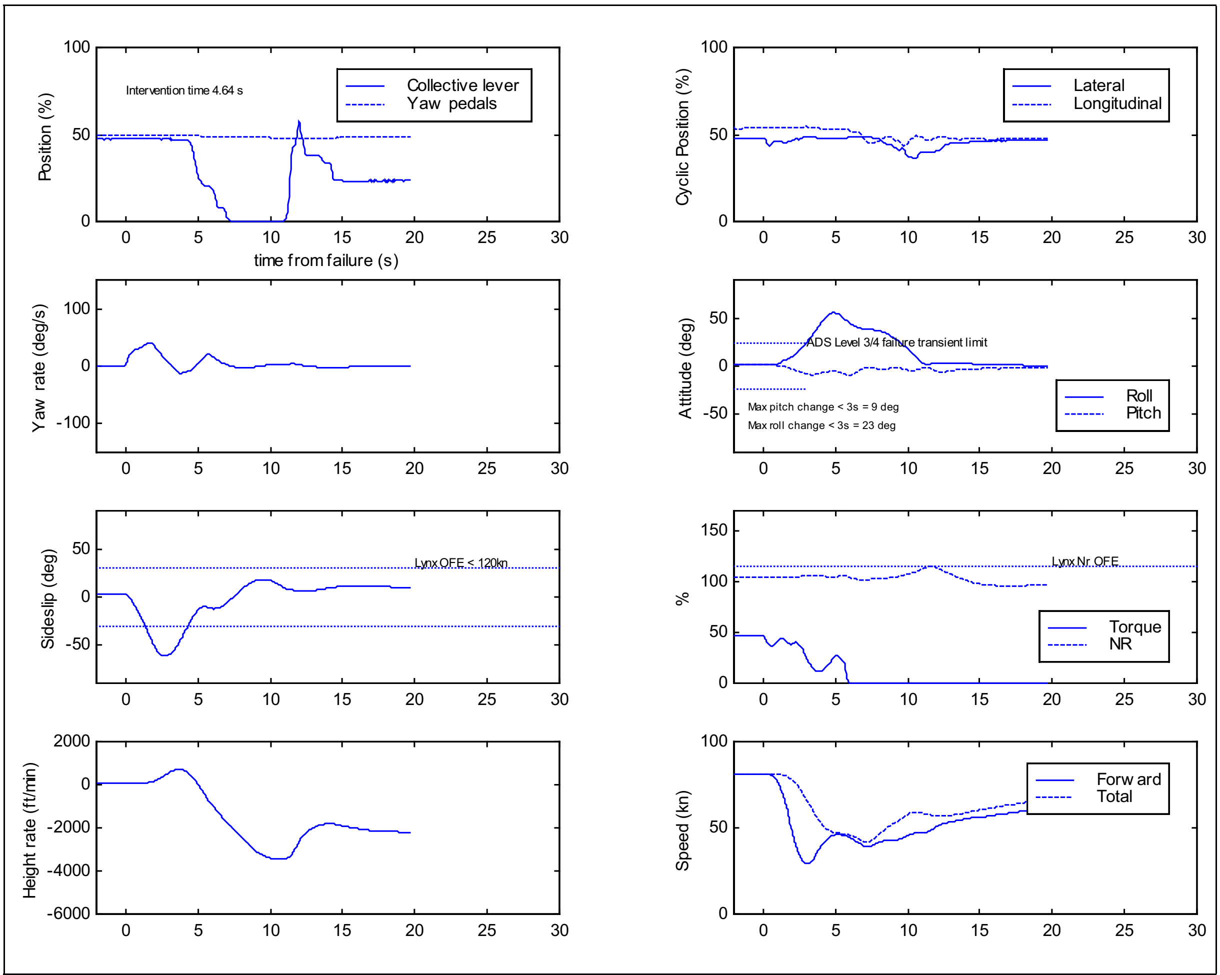

Figure 6-41 Time histories for transient phase of TRDF at mid speed (P2, enlarged fin, delayed reaction)

5.5.6 **Articulated MR**: Figure 6-42 shows results for the model with the articulated MR system. The data show a similar response level to the baseline model with a hingeless MR; the attitude hold function in the AFCS resisting the rolling moment due to sideslip. The pilot returned a Level 2 rating of 5D.

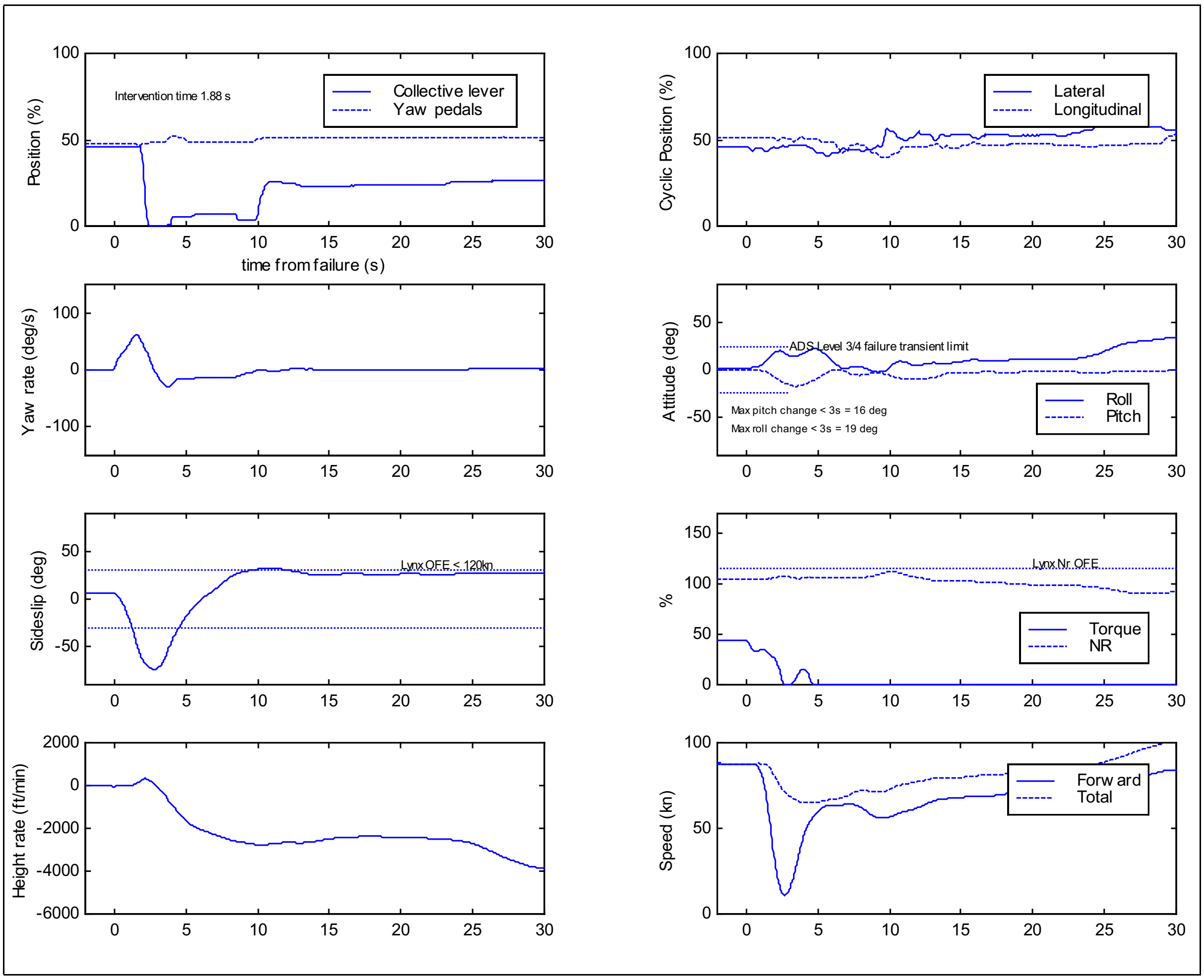

Figure 6-42 Time histories for transient phase of TRDF at mid speed (P2, articulated MR)

5.5.7 **Articulated MR and RC AFCS**: Figure 6-43 shows the articulated MR configuration with RC damping augmentation, perhaps typical of many helicopter configurations in operational service. Motions are similar to the hingeless MR case except for the large pitch-down transient of more than 30° at about 5 seconds. The pilot uses full aft cyclic to recover the aircraft and returns a Level 4 rating of 9G.

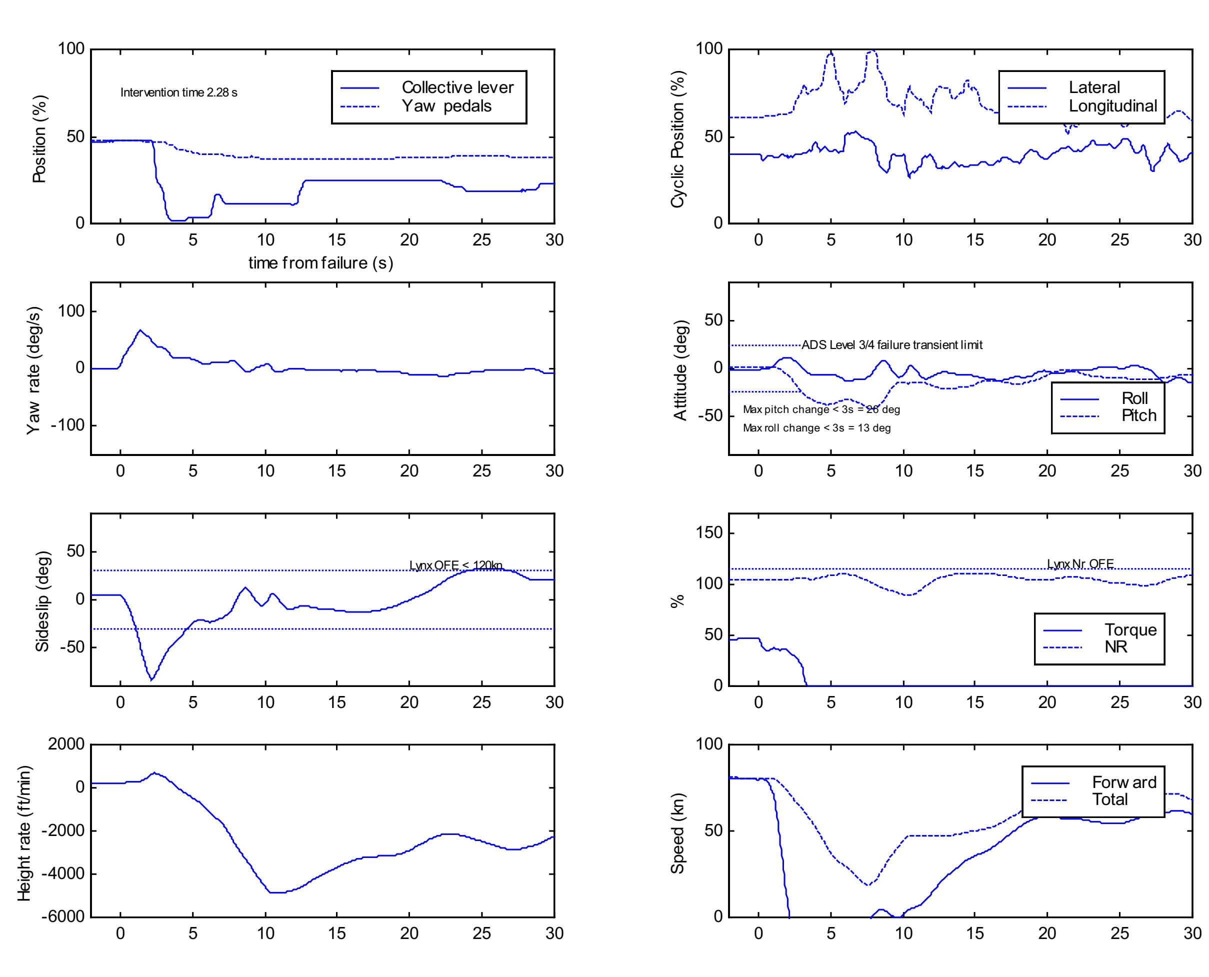

Figure 6-43 Time histories for transient phase of TRDF at mid speed (P3, articulated MR, RC AFCS)

5.5.8 **Articulated MR and delayed reaction**: Figure 6-44 shows the results for the articulated MR configuration with the pilot delaying intervention to nearly 5 seconds. The pilot's Level 3 rating of 8G indicates the severity of the failure transient.

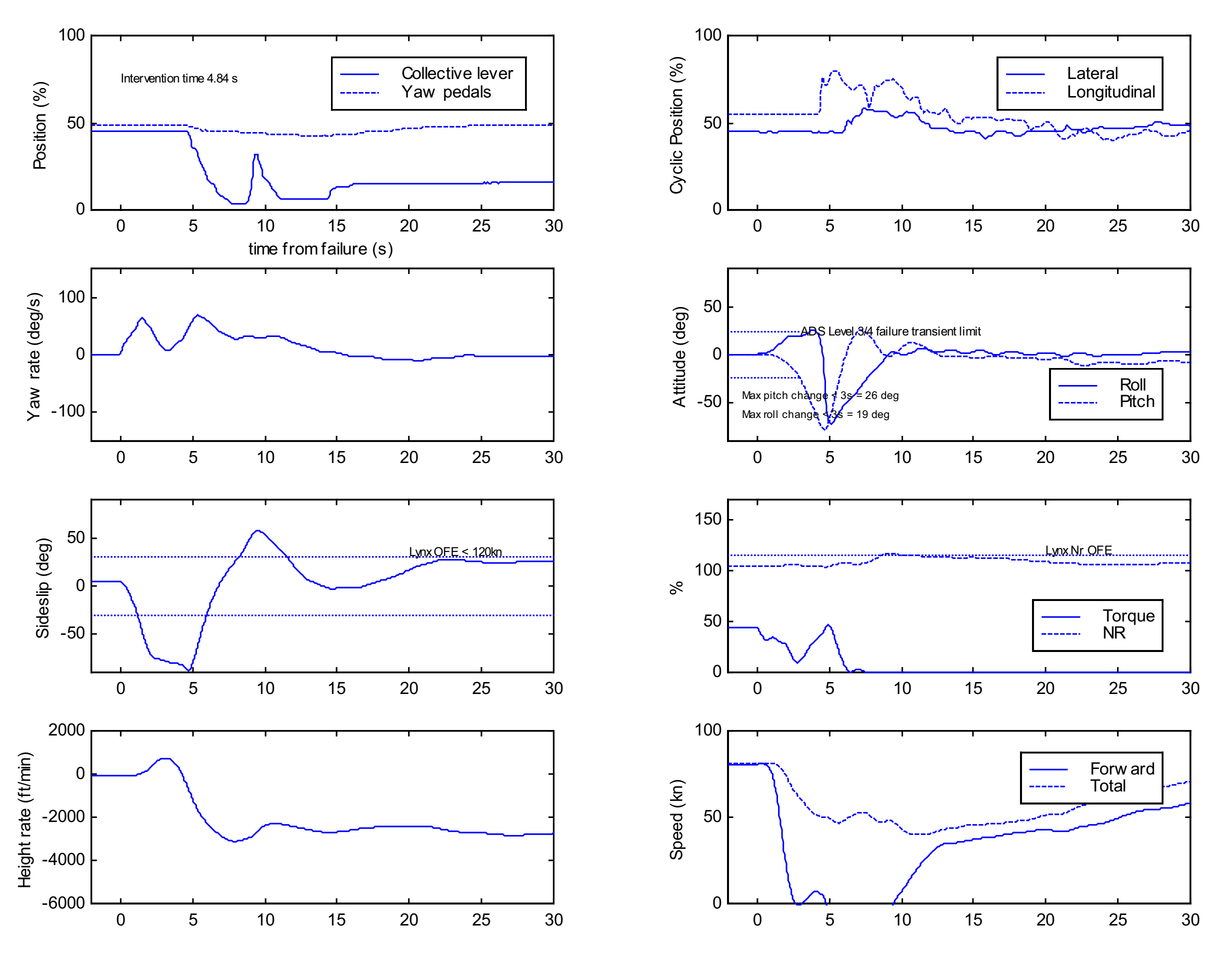

Figure 6-44 Time histories for transient phase of TRDF at mid speed (P3, articulated MR, delayed reaction)

5.5.9 **Articulated MR, enlarged fin and delayed reaction**: Finally, for the mid speed trim condition, Figure 6-45 shows results for recovery from a TRDF with the articulated MR and enlarged fin configuration with delayed reaction to see if the latter affected an otherwise expected benign transient. This case shows that the aircraft almost recovered itself from the failure although the sideslip and roll transients exceeded 50° within the first transient overshoot. The pilot rolled the aircraft to reverse the sideslip and established a new trim condition within about 12 seconds, returning a Level 2 rating of 6D.

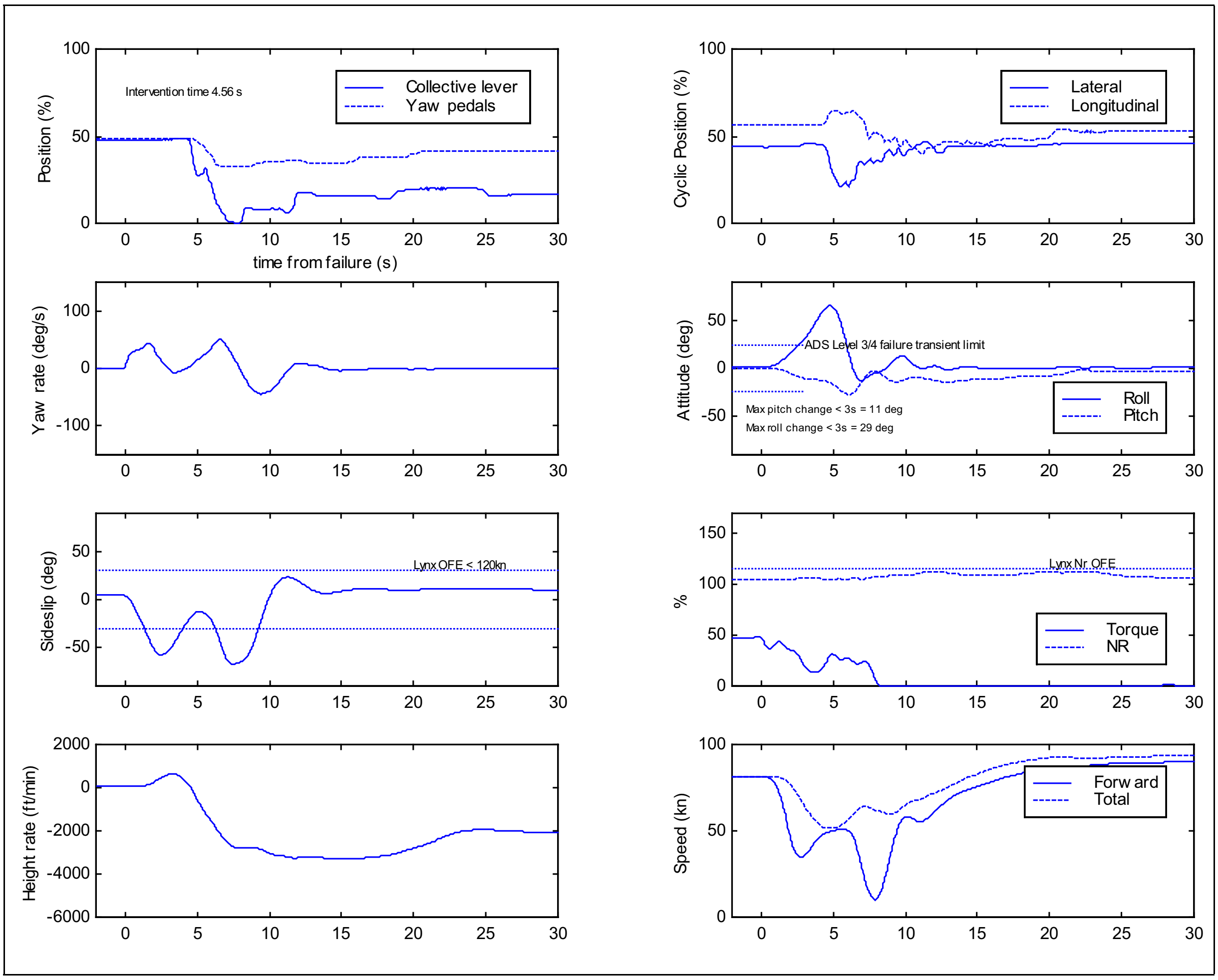

Figure 6-45 Time histories for transient phase of TRDF at mid speed (P3, articulated MR, enlarged fin, delayed reaction)

Failures at the mid speed condition proved to be more benign than at high speed as expected. The enlarged fin was again effective in reducing the sideslip transients, although not to the same extent as at high speed since the TR contributes significantly less to the anti-torque. Rapid intervention was demonstrated to be crucial for survivability, with a (delayed) PIT of 4 seconds leading to FRR G. As in the high speed failures, the MR type made little difference to the short term transient response. The deployment time ensured that the drag chute had little effect on the transients.

5.6 HP TRCFs in the hover

For the evaluation of this failure type, the pilot was required to attempt a landing directly following failure in the low hover. The HP TRCF was simulated by an increase in TR pitch to a nominal 21°, equivalent to about a 20% change from the hover flight condition. The test point time scale was set to zero at the point of touchdown. The TR pitch time histories are shown as a percentage, where 0% and 100% represent maximum (left pedal) and minimum (right pedal) pitch attainable overall; the pitch angle itself is annotated. Pilot ratings were awarded for the transient phase only.

5.6.1 **Baseline**: For the baseline configuration shown in Figure 6-46, the pilot initially pulled in collective to reduce the yaw rate but thereafter reduced collective, hence exacerbating the increasing yaw rate to port. Although the aircraft touched down (timescale defined as 0 seconds) with a vertical descent rate of about 20 ft s^{-1}, the yaw rate had increased to over 100° s^{-1}, from which the aircraft was unlikely to have survived. The pilot returned a Level 4 rating of 10H for the transient phase.

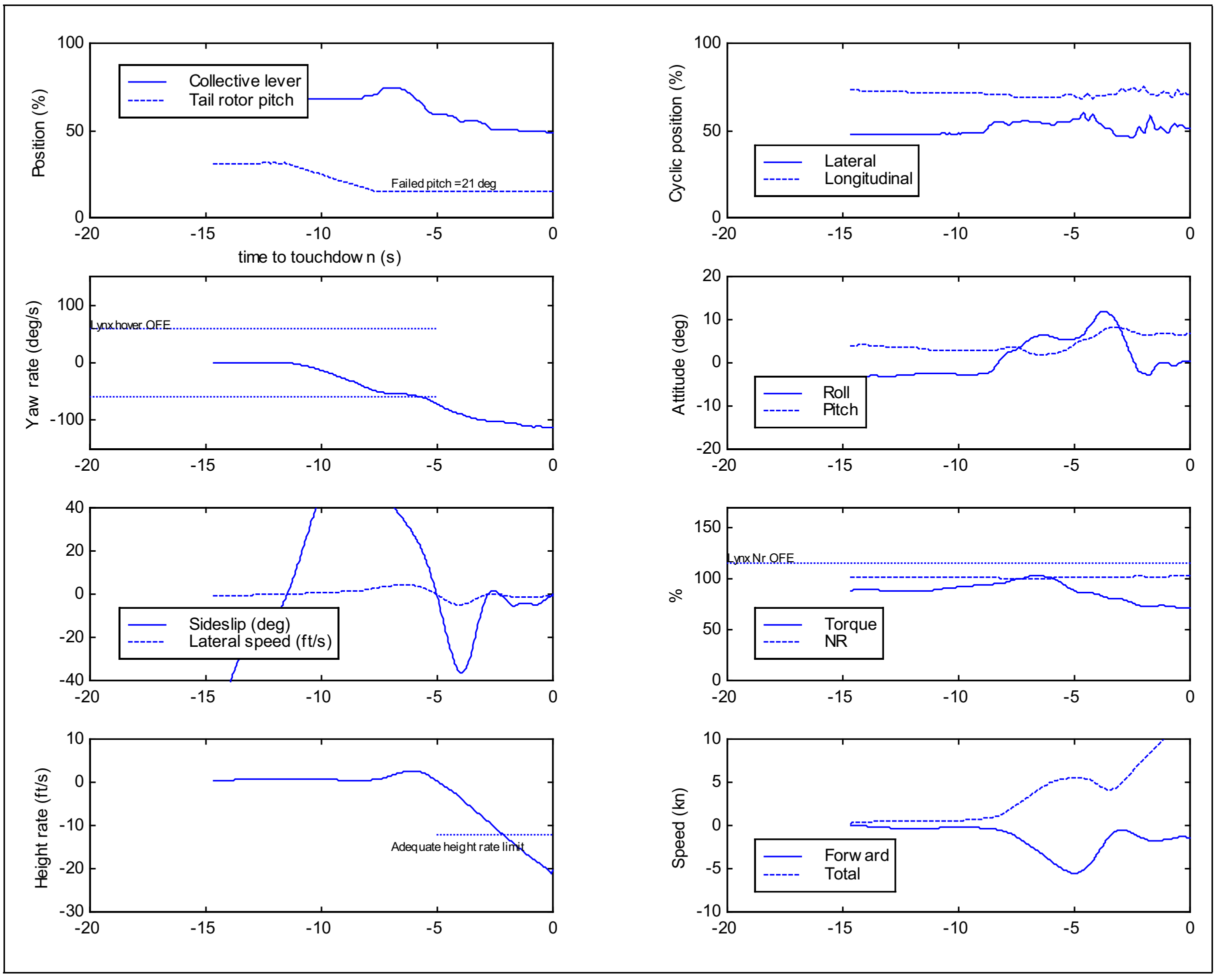

Figure 6-46 Time histories for HP TRCF in the hover (21×, P3, baseline)

5.6.2 **N_R control**: Figure 6-47 shows results for the case where the pilot reduced the MR speed in an attempt to control the yaw transient. This was successful and, about 5 seconds after the full failure, the yaw rate had reduced to below 60° s^{-1}. Just before touchdown the pilot raised the collective to cushion the landing but quickly ran out of collective pitch and the aircraft hit the ground with a vertical velocity in excess of 15ft s^{-1}. The pilot returned a Level 3 rating of 6F for the transient phase.

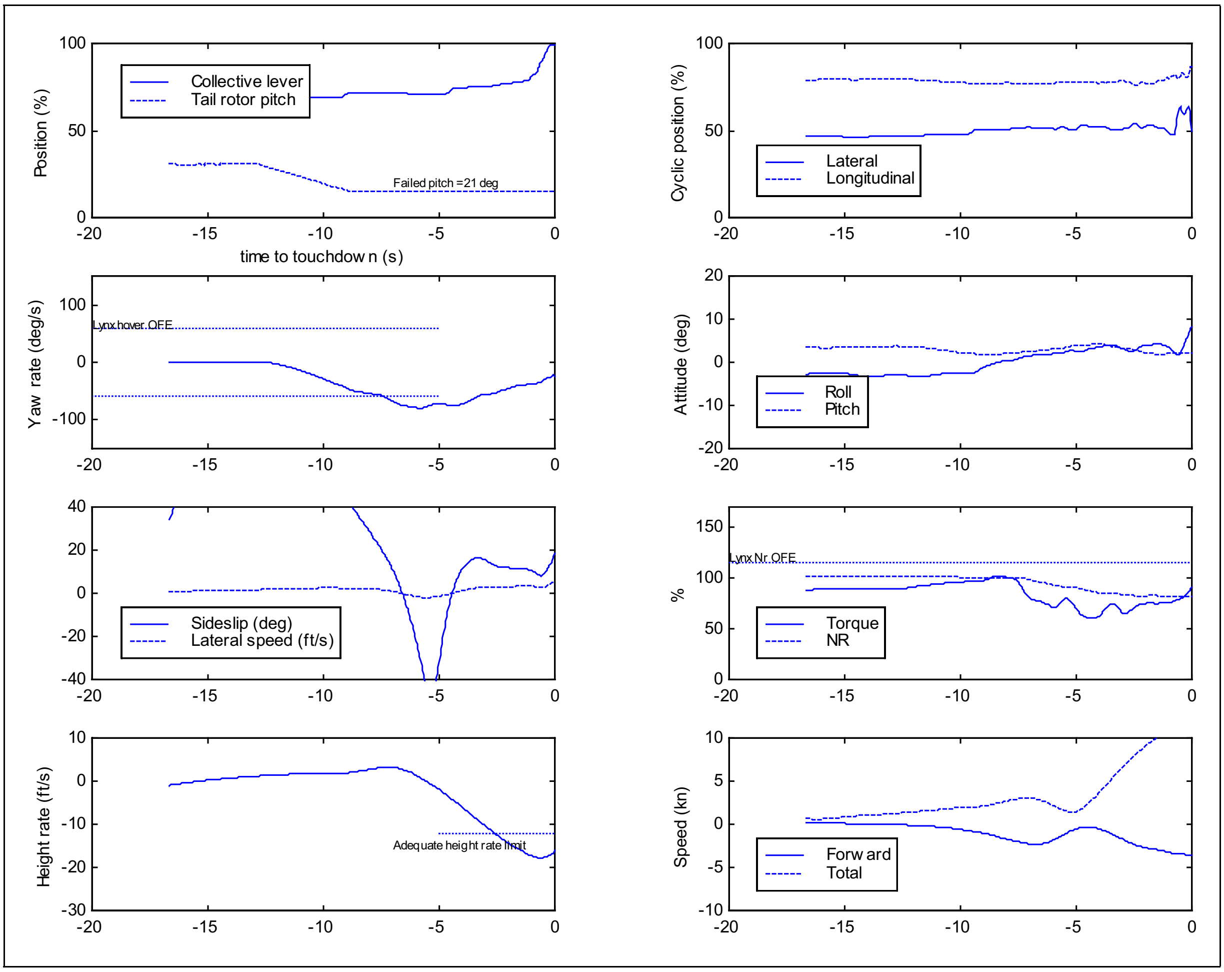

Figure 6-47 Time histories for HP TRCF in the hover (21×, P3, NR control)

The aircraft weight had originally been set to 11200 lb in an attempt to reduce the severity of HP TRCFs in the hover; this left a very small margin of collective to be used in conjunction with N_R reduction, however. In order to increase this margin, the weight of the aircraft was reduced from the baseline 11200 lb to a more Lynx-typical 10000 lb. The TR pitch freeze setting was also decreased from the 21° used previously to 19° so as to maintain the same nominal change of TR pitch on failure. The results are shown in Figure 6-48. Within 5 seconds of the full failure, the reduction in N_R enabled the pilot to re-trim in a gentle descent, albeit with significant over-controlling in collective. The pilot returned a Level 2 rating of 4C for the transient phase. Touchdown following the failure transient was accomplished well within limits. Clearly, the ability to control N_R provides the pilot with a facility to aid survival in an otherwise very difficult situation.

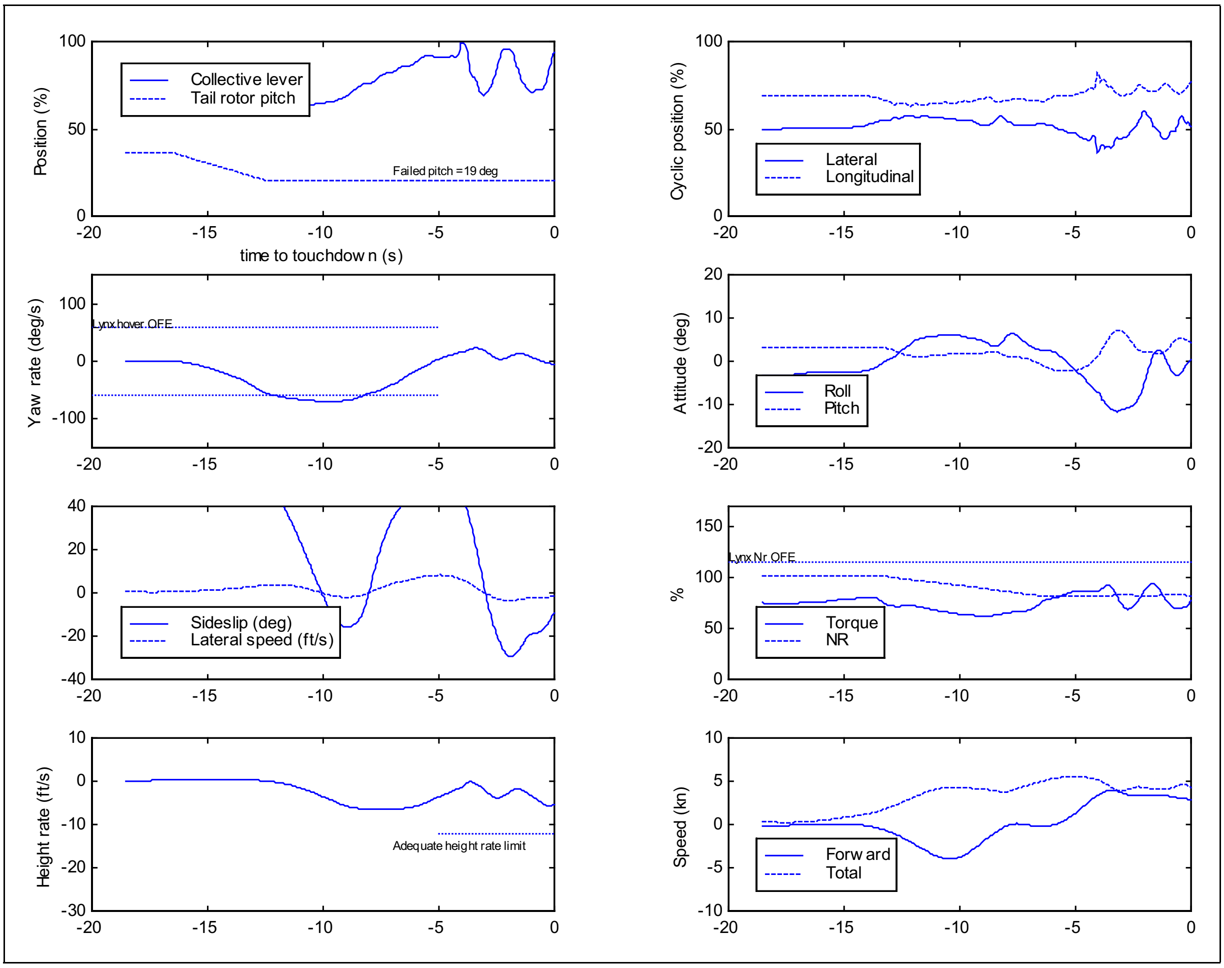

Figure 6-48 Time histories for transient phase of HP TRCF in the hover (19×, P3, NR control, reduced weight)

HP TRCFs in the hover result in a yaw rate build-up over the failure time. In the case evaluated, the failure resulted in a 20% increase in TR pitch leading to a 60° s^{-1} yaw rate. Reducing collective pitch increases the yaw rate; however, reducing MR speed, in conjunction with raising collective, proved very effective in increasing the torque from the MR and reducing TR thrust, the combination leading to a significant reduction in yaw rate and recovery from the low hover.

6 Conclusions and recommendations

Cross-references to the main text are given in parentheses.

6.1 General observations and airworthiness requirements

- **TRDFs in forward flight**: A TRDF at high speed, with a PIT of 2 seconds, results in transient sideslip that is likely to be beyond the structural limits of the aircraft. Within 3 seconds of the failure, the roll attitude increases to more than 60°, a motion that the pilots often did not give priority to counteracting, despite plentiful reserve of lateral control power. The combined sideslip/roll and reduced collective pitch, applied by the pilot to suppress the yaw transient, causes the MR to be exposed to very high angles of incidence such that the MR speed accelerates to 150% of nominal, imposing significant stresses on the MR blades and MR head.

The general character of the response was similar for both hingeless and articulated MR helicopter configurations tested (4.4.1).

Height lost during the TRDFs varied between 200 and 600 feet depending on the collective control strategy used by each of the pilots. As far as the ability of the pilot to recover from a TRDF at typical cruising speeds and altitudes is concerned, the results suggest that with a PIT of 2 seconds the following should apply (4.4.1):

- For Level 2 (adequate) handling qualities, the directional stiffness should be such that the initial transient sideslip peak is less than the OFE limit, or 30° whichever is the smaller.
- Considering the flight critical nature of the TR function, it is suggested that the handling boundary of most relevance for both low level and up-and-away flight is that between Level 3 and Level 4. Although by definition Level 3 (controllability compromised) handling qualities are unacceptable, it is recommended that for this Level, the directional stiffness should be such that the initial sideslip peak is less than that causing structural limit loads to be reached or 60° whichever is the smaller.
- In terms of transient roll response, the combined dihedral effect (which, depending on the type, may be either advantageous or adverse at the transient sideslip peak) and attitude hold function in the AFCS should be such as to contain the roll transient to less than 30° for Level 3 handling qualities and 10° for Level 2.
- There should be no requirement for engine shutdown to be part of the time critical pilot actions.
- Generally, the levels of directional stiffness which gave rise to these handling qualities during the failure transient also gave similar handling qualities during the manoeuvre and landing phases.

- **TRDFs in the hover**: With a PIT of 2 seconds there seems to be little that can be done to avoid the spin entry caused by the TRDF unless significant yaw damping can be provided. In order to recover from a TRDF in the hover (assuming height is available) with Level 2 (adequate) handling qualities, the yaw rate transient peak should be less than 120° s^{-1} (or the OFE limit, whichever is the lower), following a 2 second PIT. This result is very tentative, because only a limited number of runs were evaluated. The ability of the pilot to recover from the initial spin, and avoid entry into an even more severe flat spin by increasing forward speed, is likely to depend on the detailed aerodynamic characteristics of the fuselage and empennage (i.e. type-specific). Their interactions and the functionality of the AFCS in the pitch and roll channels will also influence the results. More work is required to firmly establish what rate of yaw transient defines the safety critical Level 2/3 boundary (4.4.2).
- **HP TRCFs**: Recovery from HP TRCFs in both forward flight and in the hover was very difficult. A failure in the hover leads to a rapid build-up in yaw and the chances of recovery without significant damage are low, even from the low hover unless a landing is made positively and rapidly. Attempts to fly out from the high hover are likely to prove very difficult. Although Level 2 handling qualities were realised with high yaw stiffness (forward flight) and damping (hover) configurations, the ability to manoeuvre away from the failure condition before landing was always questionable. The most general conclusion that can be made is that HP TRCFs lead to severely degraded handling qualities, which significantly reduces the chances of landing without incurring serious damage and/or injury (4.5).

- **LP TRCFs**: LP TRCFs are similar in some respects to TRDFs, except that the TR continues to provide some yaw stiffness and damping in forward flight and damping in the hover. The response characteristics have the same pattern as for TRDFs, although generally more benign. Although there was less coverage of the LP TRCF test points in the first trial, it is appropriate to draw similar handling qualities conclusions as for the TRDFs (4.6).
- **TP TRCFs**: TP TRCFs are very benign compared to TRDFs and the other types of TRCF and, in general, Level 1 (satisfactory) handling qualities were returned. The higher stiffness and damping configurations did not improve the pilot ratings from those of the baseline configuration and, indeed appeared to make the task a little more difficult in some cases (4.7).

6.2 Mitigating technologies

6.2.1 A number of potential mitigating technologies were explored to ease the pilot's recovery from a TRDF:

a) Minimising the PIT is crucial for survival in all TRF situations. For the baseline configuration, reducing the PIT from 2 seconds to 1 second had a significant effect on the results, although sideslip transients were still as high as 50°. Increasing the intervention time from 2 seconds to 4 seconds in the 80 kn baseline configuration TRDF resulted in controllability of the helicopter being compromised (HQR=8). Increasing the size of the fin for the same PIT restored adequate handling qualities (HQR=5). Nevertheless, a well designed warning device, which directs the pilot rapidly to the failure recovery, could be effective at reducing the PIT and aiding survival (5.4.7, 5.4.9, 5.5.4).

b) Deployable devices, like the deployable fin and drag chute, which deployed in 2 seconds were ineffective at suppressing the yaw transient, but did provide assistance to the pilot during the landing, allowing lower landing speeds. Such devices should be investigated for retrofit on existing types and incorporated in the design of future types to provide additional yaw stiffness in the event of TRF. (5.4.4, 5.4.5).

c) The 50% increase in fin size had a marked effect on the failure transient, particularly in the high speed cruise condition; all sideslip and attitude transients were within limits and the pilots returned Level 2 (adequate) HQRs, recovering to controlled autorotation within 10 seconds of the failure. The effect on inherent sideslip during autorotation can become detrimental, however, if the fin area is too large (5.4.3, 5.4.8, 5.5.5).

d) The presence of an ACAH AFCS response type, in particular when associated with 20% authority pitch/roll attitude hold led to significantly reduced roll and hence MR speed transients, particularly at high speed, but also at mid speed (5.4.6, 5.4.8, 5.5.3).

e) The variable tail boom strake concept was not covered per se in the second trial, but variation of yaw rate damping was covered in the hover during the first trial. Those results suggested that significant yaw rate damping is required to provide Level 2 handling qualities in the hover, and off-line tests suggested that such damping levels would be difficult to achieve in reality (4.2.1, 4.4.2, 5.2.3).

6.2.2 Control of MR speed and the use of a spring return system both provide assistance during TRCFs:

a) Spring return systems were not covered per se during the second trial, but the TP TRCF cases studied in the first trial suggest that setting a mid range TR pitch condition on TRCF in forward flight provides benign handling characteristics from which recovery should be made comfortably. Systems such as the SBU fitted to most UK MOD Lynx, the Negative Force Gradient (NFG) spring system fitted to UK MOD Sea Kings and Sikorsky S-61s, and the SBU spring return system fitted to UK MOD Puma helicopters and the Eurocopter AS332 work to either reduce TR control loads on hydraulic system failure, or to set a predetermined TR pitch setting on control cable failure. In both cases, the TR pitch which results is approximately that of the cruise condition, and should thus allow the aircraft to be flown at that condition. The task of bringing that condition about (i.e. managing any transients) from manoeuvring flight has not been covered in this project. Further type-specific studies should be carried out to determine the mechanisms and settings required, and to investigate the transient behaviour on TRCF and activation of the device (4.7, 5.2.2).

b) HP TRCFs in the hover result in a yaw rate build-up over the failure time. In the case evaluated, the failure resulted in a 20% increase in TR pitch leading to a 60× s-1 yaw rate. Reducing collective pitch increases the yaw rate; however, reducing MR speed, in conjunction with raising collective, proved very effective in increasing the torque from the MR and reducing TR thrust, the combination leading to a significant reduction in yaw rate and recovery from the low hover. Wherever possible, therefore, an appropriate range of MR speed control (increase and decrease from trim) should be provided to the aircrew to assist in recovery from TRCFs in the hover (5.6.2).

Section 7 Emergency procedures and advice

1 Introduction

The work reported on in this section was carried out by Westland Helicopters Limited (WHL, part of AgustaWestland) [25] and covers objective 5 as defined in Section 1. The TRF advice database analysis is described in 2. Validation of advice is discussed in 3 and summary conclusions and recommendations are given in 4 and 5 respectively. It should be noted that the QinetiQ author has made some additional recommendations relating to the manufacturers.

A total of 36 civil and military Aircrew or Flight Manual (AM/FM) TRF advice sections were analysed. The data sources included GKN Westland internal publications and external documents held at GKN WHL, the CAA and QinetiQ Bedford. This database is not considered a complete listing of all types in use at the time of publication, but does cover a wide range of categories from light single engine to multi-engine transport helicopters.

2 Analysis of the advice

The only complete method of determining the applicability of the advice given to aircrews would be to undertake a validation exercise on each aircraft type. The validation exercise cannot be generic because of the variation in possible failure modes, the basic fuselage stability and control systems characteristics. It must therefore be type-specific and is beyond the scope of this study.

To aid analysis of the failure advice and remove some of the subjectivity, the advice was reviewed using the following criteria.

- Content of advice - does the advice cover TRCFs, including disconnects and jams, and also TRDFs from hover through to forward flight?
- Detail of advice - how detailed is the advice, and how well is the information presented?
- Applicability of advice - how appropriate is the advice to the aircraft type?

Table 7-1 contains the breakdown of the advice content for both TRCFs and TRDFs. Some editorial licence has been used; for example, aircraft makes are referred to by the current manufacturer. It is apparent that all the current TRF advice covers TRDFs in forward flight and the majority (83%) discuss TRDF in the hover. However, only 67% consider any type of TRCF and only 28% discuss any type of control disconnect condition. Currently, from the details given in the AM/FM extracts, the only validated advice which can be identified is that for the Lynx. The Westland Sea King advice was, in fact, given in detail in the Flight Reference Cards rather than the AM.

Table 7-1 Content of Aircrew/Flight Manual TRF advice

Make	Type	TRCF			TRDF		
		Disconnect	**Low pitch**	**High pitch**	**Hover**	**Climb**	**Forward flight**
Agusta	A109C				•		•
Eurocopter	SA3130				•		•
	SA315				•		•
	SA341G				•	•	•
	AS332L	•	•	•			•
	AS350B2		•		•		•
	AS355N		•		•	•	•
	AS365N2				•	•	•
	EC120B				•		•
	EC135T1		•	•	•		•
	BO105		•	•	•		•
	BK117		•	•	•		•
Bell	206B	•					•
	206L		•	•	•		•
	212	•	•	•	•	•	•
	214ST	•	•	•	•	•	•
	222		•	•	•		•
	412EP	•	•	•	•	•	•
	47G						•
Enstrom	280C	•	•	•	•		•
	480		•	•	•		•
Hiller	UH12E						•
Kaman	SH2D		•	•	•	•	•
MD Helicopters	500D						•
	520N		•	•	•		•
	MD600		•	•	•		•
	MD900		•	•	•		•
Robinson	R22				•		•
	R44				•		•
Sikorsky	S61N	•			•		•
	S76C	•	•	•	•		•
	SH60B	•	•	•	•		•
Schweizer	269C (300C)						•
Westland	Lynx Mk 7	•	•	•	•		•
	Sea King		•	•	•		•
	W30		•	•	•		•
Coverage (%)		28	61	56	83	19	100

Table 7-2 considers the detail of the advice given, for example, how much help it provides to the pilot to aid identification of the problem and suggestions given to aid the pilot in recovery. The entries in Table 7-2 have been determined by categorising them under generic concepts of possible actions to be taken in the event of a TRF. For example, the column headed "Speed increase/decrease to improve/reduce fin efficiency" can be interpreted not only to include fin effects, but also to indicate that adjustments in speed can possibly improve or detract from the aircraft's state of sideslip. The table covers those details that are considered important in diagnosis and recovery following a TRF.

Table 7-1 and Table 7-2 should be viewed together because it is possible to have limited coverage but with good clarity and detail. Detailed recommendations for inclusion in the advice are given in 4, but points which stand out from Table 7-2 are that:

- Only 14% inform the pilot that loss of TR/tail pylon components will result in a change of centre of gravity that can affect aircraft pitch control.
- Only 17% discuss a defined TR pitch condition which results in the event of a control circuit disconnect.
- Only 22% of the samples viewed suggest change in vibration levels can act as a warning.
- Only 31% consider the use of main rotor (MR) speed in recovery from TRCFs.

The advice provided by Sikorsky, Bell and Westland stand out because they include very good descriptions of the possible TRF scenarios, with the Westland Lynx being the only advice claiming validation.

The final analysis was based on an assessment of the applicability of the advice to the aircraft design, in terms of the basic fuselage shape and external features. The assessment was based on engineering judgement only, and was not a rigorous mathematical analysis.

Generally speaking, where provided, the advice is appropriate, although in many cases limited. The advice for a number of aircraft suggests that a power and speed combination might be available, if not for level flight then for descent. Such advice is only likely to be appropriate for types that have particularly stable fuselage yaw characteristics. There are types where an attempt to carry this out following a TRDF would have catastrophic consequences. In general, the risk of complete loss of control is believed to outweigh the possible gain in continuing powered flight to obtain an improved landing area, especially if the advice has not been validated. Only 53% of the advice provided an indication of the appropriateness of using this strategy.

Table 7-2 Detail of Aircrew/Flight Manual TRF advice

Make	Type	A	B	C	D	E	F	G	H	I	J	K	L	M
Agusta	A109C				●			●	●	●	●			
Eurocopter	SA3130	●					●	●	●	●				
	SA315	●			●	●	●	●	●	●				
	SA341G				●		●	●	●	●	●			
	AS332L	●					●		●	●		●		●
	AS350B2				●				●	●	●			●
	AS355N	●			●				●	●	●			●
	AS365N2	●			●		●							●
	EC120B	●			●		●		●		●			
	EC135T1	●			●			●	●				●	●
	BO105	●	●		●		●	●	●				●	●
	BK117	●	●				●	●	●	●	●		●	●
Bell	206B				●			●	●		●			
	206L	●			●	●		●	●	●	●			●
	212	●		●		●		●	●	●	●			●
	214ST	●		●	●	●	●	●	●	●	●		●	●
	222	●			●	●		●	●		●			●
	412EP	●		●	●	●		●	●	●	●		●	●
	47G	●							●					
Enstrom	280C	●					●		●	●		●		●
	480	●		●	●	●	●	●	●	●	●			●
Hiller	UH12E						●		●	●				
Kaman	SH2D	●	●	●	●	●	●	●	●	●			●	●
MD Helicopters	500D				●		●	●	●					●
	520N				●			●			●		●	●
	MD600				●	●		●	●				●	●
	MD900				●			●	●				●	●
Robinson	R22	●					●	●	●					
	R44	●							●	●	●			
Sikorsky	S61N	●	●				●	●			●	●		●
	S76C		●		●		●	●	●	●		●		●
	SH60B	●			●		●	●	●	●		●		●
Schweizer	269C (300C)								●					
Westland	Lynx Mk 7	●	●		●	●	●	●	●	●	●	●	●	●
	Sea King	●	●		●	●			●	●	●		●	●
	W30	●	●		●		●	●	●	●	●		●	●
Application (%)		69	22	14	69	31	56	69	92	61	53	17	33	69

Key to column headings:

A Prompt action required to stop rotation about yaw axis.

B Increase in vibration gives a warning of impending failure.

C The aircraft pitch attitude could change following loss of tail components.

D Speed increase/decrease to improve/reduce fin efficiency.

E Use of MR speed to aid control.

F Use of cyclic to control flight path and reduce sideslip.

G Use of collective to control heading.

H Autorotation required.

I Engine off condition specified.

J Possible power and speed combination in forward flight/no power and speed combination.

K Fail-safe pitch available.

L Benefits in wind direction for landings.

M Run-on landing required.

3 Validation of aircrew advice

Ensuring that the advice given to aircrew is safe requires that a validation process be undertaken. The validation process has to be undertaken against a set of defined criteria, which should be stated with the advice given. During the Lynx validation exercise the following criteria were developed and are considered to be generally applicable[1]:

Type 1: Validation provided by a full in-flight demonstration of the recovery technique.

Type 2: Validation provided for the recovery technique being demonstrated using the best available engineering calculations coupled with piloted simulation.

Type 3: Validation provided for the recovery technique based on the best engineering calculations only.

Ideally, all validation of advice and recovery techniques should aim to achieve Type 1. However, from a practical standpoint, TRDFs can only be demonstrated by piloted simulation and, therefore, the associated recovery techniques can only achieve Type 2 validation. On this basis, the Lynx TRF advice was validated to Type 1 for TRCFs and Type 2 for TRDFs.

In order to establish validated advice to the above criteria, the following are required:

- Detailed aerodynamic data for the fuselage, for trimmed flight conditions up to ±90° incidence and ±180° sideslip.
- A full understanding of the control system and its possible failure modes.

1. In [5] the term Levels was used to denote the degree of advice validation. The term Level has been superseded by Type to avoid an association with Handling Quality Levels. Thus Level 1 is superseded by Type 1 etc

- A detailed flight mechanics model (incorporating the above aerodynamic data) coupled to a piloted simulator, with the ability to introduce random TRCFs from the control console that result in set, pre-defined TR pitch angles and simulate TRDFs.
- A flight trial on the aircraft type with the ability to simulate TRCF modes by maintaining pre-defined TR pitch angles that then enables the handling pilot to develop recovery strategies. This does require that the handling pilot has the ability to regain full control of the TR pitch if required.

Funding of such validation is a moot point. Although a manufacturer could be deemed negligent if an accident results from, or is exacerbated by, incorrect advice, manufacturers will only undertake to make advice available for all types of TRF at their own expense if mandated by the appropriate airworthiness authorities. It should be noted that successful recovery from only one occurrence could effectively repay the cost of a TRF advice validation programme.

It cannot be over-emphasised that failure to provide appropriate advice could have catastrophic consequences. For example, should the search for a power and airspeed combination be inappropriately advised for recovery from a TRDF, the sequence of events could be as follows:

a) A TRDF is diagnosed;

b) autorotation is entered and the condition stabilised;

c) power is reapplied in the attempt to find a power and speed condition;

d) the sideslip builds up, the drag increases and the speed decays;

e) the sideslip increases further without the pilot realising the deceleration and a flat spin develops.

Recovery from the flat spin in most instances is impossible.

4 Conclusions

Cross-references to the main text are given in parentheses.

- The only complete method of determining the applicability of the advice given to aircrews would be to undertake a validation exercise on each aircraft type. The validation exercise cannot be generic because of the variation in possible failure modes, the basic fuselage stability and control systems characteristics. It must therefore be type-specific and is beyond the scope of this study (2).
- The validation process has to be undertaken against a set of defined criteria, which should be stated with the advice given. Ideally, all validation of advice and recovery techniques should aim to achieve Type 1. However, from a practical standpoint, TRDFs can only be demonstrated by piloted simulation and therefore the associated recovery techniques can only achieve Type 2 validation. On this basis, the Lynx TRF advice was validated to Type 1 for TRCFs and Type 2 for TRDFs (2).
- Of the 36 types whose advice were analysed (2):
    - The standard of advice varies not only between manufacturers but also between marks of aircraft.
    - Only one provides validated advice for both TRCFs and TRDFs (Lynx).
    - The majority describe the major symptoms associated with TRDFs, however, only 14% considered the loss of components at the tail pylon and identified the possible consequences of a major change in the aircraft centre of gravity.

- Only 17% discussed a defined TR pitch condition in the event of a control circuit failure.
- Advice on the appropriateness of using a power and speed combination during recovery from a TRDF was offered by only 53%.
- Control circuit failure was not considered at all by one third.

5 Recommendations

Cross-references to the main text are given in parentheses.

- The advice given for TRFs has to be type-specific because the appropriate recovery techniques in the event of a TRF will be dependent upon the fuselage aerodynamic characteristics and anti-torque system in use. Ideally, all TRF advice should be validated to a minimum of Type 2, and Type 1 should be sought for TRCFs. The potential outcome of failing to provide appropriate advice is catastrophic, and successful recovery from only one occurrence could effectively repay the cost of a TRF advice validation programme. <u>It is strongly recommended therefore that type-specific piloted simulation and, where possible, flight test programmes are put in place to achieve this (2, 3).</u>
- The variation in the standard of advice would suggest that there is considerable room for improving the level of advice currently given in the AM/FMs. In particular (2):
  - The advice should make clear whether the use of a power and speed combination is appropriate or not during recovery from TRDFs.
  - The advice should contain information on techniques required to control the descent.
  - The loss of tail pylon/TR components should be identified as a source of possible aircraft pitch control problems.
  - Unusual vibrations emanating from the TR area of the helicopter should be identified as being indicative of a possible TR problem and pilots should be advised to set up a minimum power condition if in forward flight, or to land and shut down for technical investigation if in the hover.
  - Unusual pedal positions should be identified as a possible impending TRF condition. The advice should recommend setting up a minimum power condition if in forward flight, or to land and shut down for technical investigation if in the hover.
  - The effects of a TR control circuit disconnect on the TR pitch condition should be identified.
  - Subject to validation, and where appropriate to the type (i.e. where the pilot has the ability to control rotor speed), the benefit of varying MR speed in the hover following a TRCF should be reflected in the advice.
- Simulation of the TRDF conditions should be undertaken using high fidelity flight mechanics models to ensure any recommendations to seek a power and speed combination are justified (3).
- There should be a requirement for the manufacturers to identify the possible failure modes of the TR control circuit, and the impact of TRFs on the anti-torque moment supplied by the TR so that appropriate advice can be generated. It is also recommended that manufacturers be mandated to provide validated advice for all types (3).

Section 8 Training

1 Introduction

The work reported on in this section covers objective 6 as defined in Section 1. Data gathering is described in 2, training simulator requirements are discussed in 3 and the assessments of visited training simulator facilities provided in 4. Analysis of the responses to a training simulator questionnaire is given in 5. Flight training and general awareness are covered in brief in 6 and 7 respectively. Summary conclusions and recommendations are provided in 8 and 9 respectively.

Regular focussed training is essential for the efficient application of emergency procedures. This is particularly important for the helicopter pilot who, in many cases, will be flying a vehicle with inherently unstable aerodynamic characteristics, with significant cross-coupled control requirements even when aided by an Automatic Flight Control System (AFCS). Where provided, such training promotes instinctive diagnosis and application of recovery techniques and, particularly in the case of TRFs, rapid application of the appropriate technique, which can make the difference between recovery and catastrophe. In order for these techniques to be both appropriate and instinctive, the training must be structured, regular, and conducted using a facility providing sufficient realism. Clearly the most realistic training is conducted in the air, but simulation provides the next best level of training value and, in many cases, the most appropriate. The quality of the overall training is the combined fidelity of the simulation model, the cockpit layout, motion and visual systems and, not least, the training methodology. The aim of Section 8 is to present the reader with an appreciation of current TRF training across the UK MOD and civil organisations, and to highlight and recommend good practice.

2 Data gathering

In order to qualify the conclusions and recommendations of this review, three visits to training establishments (used for the UK MOD) were arranged with the primary aim of assessing the simulation facility. To supplement these visits a questionnaire was sent to a selection of civilian and military instruction centres to elicit general information on the capabilities of and the strategies for current TRF instruction.

3 Simulator requirements

3.1 Motion and visual systems

Appropriate diagnosis and recovery from TRFs is heavily dependent upon the pilot receiving visual and motion cues. A motion system of some sort is therefore essential. Such systems usually have the full six degrees of freedom (DOF) (surge, sway, heave, roll, pitch and yaw) or only three DOF (e.g. heave, roll and pitch). A three DOF system typically lacks yaw motion, however, which is significant for simulation of hover TRFs in particular, and a six DOF system is therefore preferable. Visual cues are particularly important when close to the ground, such as TRFs in the low hover, and during the latter stages of all recoveries and a suitably large vertical field of view becomes important. The representation of secondary visual cues, in addition to the overall field of view, are therefore advantageous in this respect; e.g. lower side or cockpit chin windows, where ground speed and lateral velocity cues would be provided.

3.2 Certification

Current civil rotorcraft criteria for simulation validation are embodied in a Federal Aviation Administration Advisory Circular [26], which addresses fidelity of the air vehicle model, and the visual, motion and other simulation systems. Significant interest in these criteria exists within MOD, and they have been proposed on a number of UK military rotorcraft simulator programmes to support the acceptance process. However, further research is required to understand how they should be applied to the various military roles [27].

The degree to which a simulator manufacturer is required to demonstrate compliance is determined by the type of device being constructed, of which the following are currently defined [28]:

Level A: Reserved for future low-level devices but represents the lowest level of simulation fidelity.

Level B: Sufficient fidelity to support partial pilot training and checking excluding hover and low-speed flight.

Level C: Sufficient fidelity to support complete pilot transition training and checking.

Level D: Sufficient fidelity to support complete initial pilot training and checking.

Compliance of the mathematical model is demonstrated through comparison of simulation and flight test time responses for a variety of input types and flight conditions, divided into categories for performance and handling qualities.

The criteria for performance and handling qualities are expressed in terms of tolerances on parameters which would be readily measurable in a suitably instrumented aircraft; for example, vehicle responses to control inputs typically must be within 10% of those observed in flight test and the trimmed control settings within 5% of flight for level, climbing and descending flight. Undoubtedly, these tolerances make significant demands on current generation modelling technology. Although they are probably sufficient for civil operations, their suitability for acceptance of military simulations has yet to be fully determined.

A standard for aeroplane flight simulators exists under the auspices of the Joint Aviation Authorities Committee [29] which also defines four Levels, and a document for helicopter flight simulators is in preparation [30], which defines Levels A to D very much like that of [26]. For example, in both the US and proposed European rotorcraft documents, Level D cannot be awarded unless the continuous vertical field of view is at least 60°. Abnormal/emergency procedure subjective testing defined in [30] includes directional control malfunctions in the hover and cruise, during visual approaches and landing. Aural cues and antitorque ineffectiveness tests are also specified.

A summary of all the current civil and military flight simulators were obtained from [31] and [32] respectively. No certification information was provided for the military facilities, and of the civil facilities, only one (FlightSafety International Bell 412/212, Fort Worth, 1998) has been *certified* to Level D. Five more are expected to be awarded Level D standard (FlightSafety International and HELISIM) during the next two years. The first of several Level C certifications (SAS Flight Academy Bell 412/212, Stockholm) was awarded in 1998 [33,34]. It should be noted that in this case the

40° continuous vertical field of view was insufficient to attract a Level D standard, even though two chin window views were also fitted.

It is recommended that all facilities aim to achieve Level D standard, and it is likely that TRF training cannot be carried out with sufficient realism unless the simulator is of at least Level C standard. Note that replication of the actual aircraft field of view, including separate screens to represent chin windows, for example, could conceivably fail to meet the Level D minimum continuous field of view requirements. It is recommended that the standards authorities revise these requirements, so that replication of the actual aircraft field of view is sufficient for Level D standard. It should be noted that although as yet uncertified, the QinetiQ Bedford AFS (on which all MOD and CAA TRF simulation studies to date have been conducted) is of Level C standard.

The data provided in [32] indicate the investment that the UK MOD is making in simulation; the complement of existing and planned military helicopter motion-based simulators will number 17, the same as for the rest of Europe put together.

3.3 TRF fidelity

The nature of TRFs, as featured in Sections 2 and 6, is type-specific and necessitates expansion of the flight envelope typically validated for training. In particular, the aerodynamic modelling of the airframe needs to be applicable to large angles of incidence and sideslip, (Lynx look-up tables were formulated from model wind tunnel tests over ranges of ±90° incidence and of ±180° sideslip [5]). More complicated would be the inclusion of the effects of yaw rate and aerodynamic interactions (main rotor (MR)/TR, MR/empennage) and it remains to be seen (from ongoing and planned QinetiQ activities) how beneficial they are.

Validation of the overall training facility is critical to its effectiveness, particularly with respect to TRFs where inappropriate actions can rapidly exacerbate the problems encountered. Where validated TRF advice is available, all relevant facilities should be validated against it, otherwise there is a danger that other techniques that appear to work in the simulator, may not work in the real aircraft.

4 Training simulator assessments

Three simulators were assessed by a Westland Helicopters Limited (WHL, part of AgustaWestland) test pilot who was experienced in the assessment of simulators and familiar with TRF strategies from previous work with QinetiQ Bedford. The simulators visited were those used by the test pilot for routine annual or biennial training as part of his flying duties with the company, and are detailed in Table 8-1. It should be noted that the Lynx HAS Mk 3 facility is now located at RNAS Yeovilton. The previous TRF work had concentrated on providing validated aircrew advice for the Lynx. Therefore when appraising the simulators of other aircraft a certain amount of technical judgement was used, especially in identifying the fidelity of the aircraft response following a TRF.

Table 8-1 UK MOD training simulators subject to assessment

Date	Aircraft Type	Operator	Location
April 1998	Lynx HAS Mk 3	Royal Navy	Portland, UK
August 1998	Sea King HAR Mk 3	Royal Air Force	St Mawgan, UK
August 1999	Super Puma (for Puma HC Mk 1)	Helikopter Services	Stavanger, Norway

4.1 **Assessment technique**: The following tests, which were subjective and qualitative, were carried out to compare the simulator to the aircraft modelled:

- **Primary flying control characteristics**: Where possible, before starting rotors, the primary flying control throws, cyclic trim gradients, frictions and dynamics were assessed.
- **Low speed manoeuvres**: After take-off, the visual and motion cues, the sideforce cues and simulator aircraft attitudes were assessed in the hover, sideways and fore/aft flight and in spot turns.
- **Forward flight**: In order to compare the roll and yaw stability characteristics of the models in forward flight with those of the associated aircraft, steady heading sideslips (SHSSs) and turns on one control using lateral cyclic (TO1C – LatCyc) were carried out in level flight, climbs and in autorotation.
  - In SHSSs, sideslip is induced by a constant pedal input and the horizontal flight path is maintained by use of lateral cyclic; usually a right pedal input with left cyclic deflection will maintain the horizontal flight path with left sideslip and vice versa.
  - In TO1C - LatCyc, rolling into a turn with collective lever and yaw pedals held constant allows the tendency for adverse/proverse yaw to be assessed. Once at a steady bank angle, the position of the cyclic stick relative to the level flight position yields an indication of spiral stability.

  Although not carried out for these assessments, it is recommended that in future tests, TO1C using pedals only are also carried out to provide an indication of the roll rate to be anticipated as sideslip develops in the transient phase of a TRF.
- **TRDFs**: TRDFs and subsequent handling were assessed in the hover and in forward flight at various TR pitch settings, the directional stability of the fuselage with the TR stopped being of particular relevance. This was because, if the directional stiffness of the model was higher than that of the aircraft, the model would handle more benignly following a TRDF than would the aircraft.
- **TRCFs**: TRCFs and the subsequent handling were assessed in the hover and in forward flight at various TR pitch settings.

4.2 **Lynx HAS Mk 3 (RNAS Portland)**: The Lynx simulator is obsolescent with a basic 4 axis motion system, a simple aircraft model and night/dusk SP1T visual system. However, the cockpit is representative and the facility provided an acceptable training mimic of the aircraft throughout the flight envelope up to 30° angle of bank (AOB). The simulator staff were anxious to improve the standard of the simulation; for example they wanted to know what the real aircraft's slip-ball did in spot turns. As observed, the dominant effect on the slip ball is gravity and the slip-ball normally "sits" in the lowest point of its track, only altering its position slightly under the effects of angular acceleration.

As regards the simulation of TRFs, the simulator staff had removed the post-TRDF exercises because of over-benign handling following TRDF (there was too much directional stiffness following TRDF). However, TRCFs are dealt with thoroughly and were assessed to be realistic. The simulator responded in a logical way to medium, high and low pitch TRCFs flown in the hover and in forward flight. For a fixed TR pitch setting, the model's TR thrust varied predictably with MR rpm. The staff used this feature to replicate an actual high pitch TRCF that had occurred to an aircraft at the base [14]. This had been handled successfully using the methods defined in the QinetiQ Lynx flight trial [5] (carried out in conjunction with an AFS trial). In the actual incident, a reduction in MR rpm (using the Speed Select Lever (SSL)), whilst maintaining constant power, increased the MR torque thereby reducing the resultant yaw moment and hence yaw rate. The benefit of having conducted the flight trial was that it provided data and validated advice against which to rate the simulator's behaviour, and hence a measure of confidence to provide to the aircrews. The availability of previous occurrence data also provided additional confidence. The only TRF training that was assessed as dubious was the tentative advice for handling a high TR pitch malfunction in forward flight. The method proposed is to retard the engine condition levers to limit the engine power output and then over-pitch the MR to reduce the MR rpm to well below the normal power-on minimum rpm of 95%. This is dubious because there is no allowance given by the DA or given in the MAR for operation of the engines in flight with the ECL between the flight gate and the ground gate. In this condition, automatic governing of the rotor is not available and to carry out the drill successfully it is considered that it would require well above-average piloting skills. There is as much risk in carrying out this drill as there is from the TRF itself, since if the MR speed is allowed to decay too far, control of the helicopter will be lost.

Although this simulator is old, the well-motivated staff in current or recent flying practice are making best use of it. The re-run of the actual incident was very valuable and other simulator facilities should copy this idea. With the increased use of HUMS, Cockpit Voice Recorders (CVRs) and Accident/Flight Data Recorders (ADR/FDRs), much more detailed data will become available for simulator use. The requirement to be able to control the MR rpm over a significant band (95 – 105%) to greatly increase the chance of handling a TRCF successfully, was reinforced during this assessment. This is particularly the case if the MR rpm datum controller is within easy reach of the flying pilot (preferably on the collective lever handgrip).

4.3 **Sea King HAR Mk3 (RAF St Mawgan)**: The Sea King simulator at RAF St Mawgan was commissioned in 1996. It has a very modern control room with a touch-screen control system that includes a replay facility, and the capability to display and print out the parameters of a demonstration point for the controller. The facility has a contemporary 6 axis motion system and an accurately detailed cockpit that can be configured to represent either a Sea King HAR Mk 3 or a Mk 3A. The simulator was supplied by Thomson Training and Simulation Ltd (now THALES) and their model uses basic Sea King flight mechanics parameters supplied by WHL. The visual system (SP3T/200) can replicate light levels from overcast day through dusk to night with visibility variable from clear through mist to fog and snow. In particular, the airfield surfaces are very realistically textured.

The primary flight controls were found to be realistic, except that the longitudinal cyclic stick's response to a "stick rap" is more damped than the aircraft's response. In addition, the yaw pedals have a noticeable second stop, which was designed to trip the motion in the event of too large a yaw demand. In low speed manoeuvres, there is a residual damped attitude oscillation following harsh manoeuvring.

From the hover, TRDF simulations are thought to be realistic but of short duration. The ability to replay the event to the student in slower time while in the simulator might be a useful teaching aid. Several actual Sea King TRDFs featured "clean breaks" of the drive shaft couplings that allowed for a finite run-down time during which the pilot was able to hold heading briefly by applying increasing left pedal. When full left pedal was reached the aircraft spun to the right. All simulators should be able to replicate this type of failure with variable run-down time where appropriate.

Entry into autorotation following TRDFs in forward flight is more problematic because there is a damped yaw oscillation that lasts several seconds. Handling could only be assessed once the oscillation had stopped. Once in autorotation with the TR stopped, directional stability seemed excessive. Balanced flight can be maintained down to 30 kn airspeed. After autorotating, power was applied to see if a power/speed combination could be found that would allow for continued flight. At 80 kn airspeed 80% twin engine torque could be applied without yaw divergence. This was considered to be optimistic. If no attempt is made to continue with powered flight, a seemingly realistic simulated engine-off landing can be made. An enhancing feature of the motion and, in particular the visual system, is that the crashes are very realistically represented.

The responses to medium, high and low pitch freeze TRCFs were assessed as logical. From previously flown Sea King training flights, when MR rpm was altered with fixed collective lever and TR pitch, it was thought likely that Sea King TRCFs could be controlled in a similar manner to the Lynx. The Sea King simulator responded to changes in MR rpm in the same way as the Lynx aircraft; however, this method is not taught.

Overall, the simulator training was basically sound with the exception of the yaw oscillation seen on entry to autorotation following a TRDF in forward flight and the concern about the directional stiffness of the fuselage with the TR stopped. As with the other simulators, some form of validation of the TRF training should be considered. The staff are all in recent or current flying practice and are keen to make the training as realistic and practical as possible. There is the potential to give students a printed time history of specific training items. The concept of giving the students a passive replay of training points should be considered.

4.4 **Puma HC Mk 1 (Stavanger)**: The Puma HC Mk 1 training is given in an obsolescent Super Puma simulator (commissioned in 1984) with a basic 6 axis motion system and model, and a night only visual scene. The visual system is an SP1 with a 150° horizontal field of view. The assessing pilot was not familiar with the primary flying controls in the detailed Super Puma cockpit but they appeared to mimic those of the Puma sufficiently well to be of no hindrance.

The assessment of TRDFs was carried out from the hover and forward flight. No TR run-down time could be simulated after the TRDF. The response to the failure and to the subsequent control inputs appeared logical. In the hover there are usually good visual cues to back up the yaw motion cues. In forward flight the motion provides good yaw and sideforce cues; visual cues can be minimal if the failure occurs when the field of view does not include any cultural lighting on the ground. In forward flight, if the vital action of "lower the collective lever fully" are not carried out promptly, the yaw angle increases rapidly causing controlled flight to be lost through roll divergence. This is a known feature of the Puma family in which the rolling moment due to lateral velocity can exceed the maximum lateral control moment that can be produced. It was not determined if the modelled fin size of the Super Puma was reduced for the Puma HC Mk 1 training. There was anecdotal evidence from pilots who had suffered TRDFs in the hover in the Puma, and who had been trained in this simulator, that the TRDF training was effective. From this evidence it has been identified that it is the auditory cue of the drive shaft shearing and the fuselage yaw motion that provided the immediate diagnosis of the failure, but it was the simulator training that provided the instinct to then immediately lower the collective lever. The essence of useful simulator training is to provide as realistic symptoms as possible to enable pilots to diagnose the failure accurately and then, having made the correct diagnosis, to apply the "vital actions" promptly and instinctively.

TRCFs were flown in the hover and in forward flight. The simulator features a SBU as fitted to the Super Puma but not, at the time of writing, to the Puma HC Mk 1. The response to the failures and the subsequent control inputs appeared logical. The SBU greatly improves the chance of a successful landing. In order to test the modelling of TR thrust, the MR rpm was reduced by retarding the Engine Control Levers with the collective pitch and TR pitch held constant. As rpm was reduced the aircraft yawed in the anticipated direction (left). Although the Puma HC Mk 1 has no means of increasing the MR rpm datum, it is thought likely that this method could be used in the aircraft to counter a high pitch freeze TRCF.

Despite the cockpit and model not being identical to the Puma HC Mk 1, the TRDF training had been proved effective in the real world. Although the simulator does not provide the audio cue of the TRDF, the visual and motion system is thought to provide enough realism to help diagnosis of the failures and enforce the need for the rapid and instinctive reaction required. There may be a wide range of sounds associated with the various causes of TRDF, but if examples of such noise and vibration are recorded on a Cockpit Voice Recorder (CVR), HUMS or an ADR/FDR this could be included in the appropriate simulators.

4.5 Recommendations

- The three training simulators reviewed were assessed as providing useful training. The value of simulator training could be improved based on the following recommendations (ordered by their referenced paragraph):
  - The models' failure handling characteristics should be validated (where possible) against flight data (4.2).
  - Data from previous TR accidents and incidents should be utilised to enable these occurrences to be accurately reproduced in simulators (4.2).
  - Where possible, variation of rotor speed should be explored for recovery from TRCFs (4.2).
  - TRDFs should be demonstrated with both zero run-down time and a short rundown time (4.3).
  - Event replays in real-time or slow time, graphical displays of time histories of aircraft dynamic and control inputs that could be displayed will aid an appreciation of the failure handling (4.3).
  - The recognition of the failure symptoms and the correct crew diagnosis and initial reaction should be the prime aim of the training (4.4).
  - Where possible, examples of the sound and vibration associated with TRDFs should be captured or simulated for inclusion in training (4.4).

5 Training simulator questionnaire

To supplement the work of assessing the training simulators and to obtain a broader understanding of the facilities and organisations involved in aircrew training, a questionnaire was sent to both civilian and military operators. The respondents are listed in Table 8-2. It should be noted that none were approved according to the Levels A-D defined in [26], although the FlightSafety International S-76C facility has since been certified to Level D standard.

Table 8-2 Training simulator questionnaire respondents

Type	Mark	Operator	Location
AS332		Helikopter Service A/S	Stavanger, Norway
Lynx	AH Mk 7	British Army	Wattisham, UK
Lynx	AH Mk 7/9	British Army	Middle Wallop, UK
Lynx	HAS Mk 3(s)	Royal Navy	RNAS Yeovilton, UK
S61	N	Scotia Helicopter Services	Aberdeen, UK
S61	N	Helikopter Service A/S	Stavanger, Norway
S76	C/IIDS	FlightSafety International	Palm Beach, USA
Sea King	HAR Mk 3/3a	Royal Air Force	RAF St. Mawgan, UK
Sea King	Mk 6	Royal Navy	RNAS Culdrose, UK

The questionnaire covered 4 main areas:

a) General information about the simulated type and training organisation;

b) details of the simulator motion and visual systems;

c) general training policy and tasks;

d) TRF training modelling and strategy.

It was stressed in the questionnaire that specific details would not be published about any individual training facility or organisation and the analysis has drawn generalisations from the data. The replies received were thoughtfully completed with additional information being volunteered in some cases. The questionnaire was not completed in its entirety by all participants and thus some statistics are stated on an 'at least' basis.

5.1 The simulators

Five of the nine simulators were commissioned in the 1980s, and two each in the 1970s and 1990s. All were manufactured by companies now part of Thomson Training and Simulation Limited except one, manufactured by FlightSafety International. Two thirds use a six DOF motion system, the remainder using a 3 DOF system. The four that provided information about the field of view have at least 40° elevation and 150° azimuth. All use a Computer Generated Imagery system. Two thirds reported some degree of validation based on flight data, but only over the Operational Flight Envelope (OFE). In one case One Engine Inoperative conditions are also stated as having been validated, and in another, TRFs are specifically stated as not having been validated (it is likely that this is the case for all but the Lynx simulators). Only one states that validation has been carried out against another simulator. All are subject to engineering and standards inspections.

5.2 General simulator training

All of the simulators are staffed by qualified instructors working for the relevant Service or owning company, and have their training policy and syllabus directed by their Service or company/civil authority. At least 5 (56%) conduct basic training, 4 (44%) conversion to type training and all provide continuation and/or refresher training. At least 4 (44%) provide training specifically for instructors. All provide dedicated and unannounced emergency training. On average 9 hours training per pilot per year are carried out, totalling 2500 hours per year. Integrated ground school support is provided by 7 (78%), the other 2 (22%) providing it on an individual requirement basis.

5.3 TRF training

All of the trainers provide some form of TRCF and TRDF simulator training, although this is not a formal part of the syllabus in at least one case. Cable and/or hydraulic TRCFs are covered in 7 (78%) cases while 8 (89%) provide pitch freeze TRCFs.

Very little was revealed on how the TRFs were modelled, but it is expected to be similar to that employed in the QinetiQ Bedford AFS, whether validated or not. In the case of the Sea King facility at RAF St. Mawgan, the TR pitch can be frozen at any power setting and, for cable failure, the pitch is normally governed by the Negative Force Gradient (NFG) spring. This facility was the only one providing information on Pilot Intervention Time (instantaneous, and likely to be the case for the others) and TR run-down time (dependant on the conditions at the point of failure).

At least 4 (44%) provide instruction on TRF diagnosis and recovery and at least 7 (78%) include reference to Aircrew or Flight Manuals (AM/FMs) and Flight Reference Cards. Strategy source is a mixture of experience, AM/FMs and simulation, in addition to Royal Air Force Handling Squadron (RAFHS) for the UK military facilities. Strategy approval is provided by the training organisation, plus QinetiQ Boscombe Down for UK military.

Very little was provided regarding overall and TRF-specific training effectiveness and fidelity; one assessed by an external agency was thought to be poor due to lack of simulation fidelity. Others were thought to be effective (the rate of recovery from simulated TRFs being improved dramatically by the training provided), but lacked validation. The highest confidence is thought to lie with the Lynx simulators due to the techniques having been validated through QinetiQ/WHL flight test and AFS studies.

6 Flight training

Only very limited training can be carried out in the aircraft. The only manoeuvre that can be practised is a yaw control jam, although a LP jam could indicate some of the effects of a TRDF. Such a failure is simulated by the instructor putting his feet on the pedals at a given setting. The student is then required to fly the aircraft either to a hover (which is possible in the BO105 and, occasionally, the Dauphin) or to a simulated running landing. Control is normally taken back by the instructor just before landing, to avoid any possibility of inadvertent ground contact. Yaw inputs are unavoidably made on operation of the collective where a collective-yaw interlink is fitted. Maximum value is therefore not normally achievable from the exercise. In the past, the practice of TR malfunctions was not a regulatory requirement for private or commercial licences in the UK, although whether this was due to a perceived lack of need, the obvious difficulty in carrying out the practice, or commercial pressure is not clear. Since July 2000, the requirement for licence skill testing (award of a type into the licence) and licence proficiency checking (annual proficiency once qualified on a type) purposes (whether private or public transport) is contained in appendices 2 (items 3.3.14 and 3.3.15) and 3 (items 7.14 and 7.15) to JAR-FCL 2.240. Both of these references require that a minimum of three items from within the group of emergencies are chosen for each check and the CAA (as the UK Authority) are making public transport operators include all of the items in the group as part of a rolling programme of checking, so that all emergencies are checked over a period of time.

A survey of all helicopter schools was not carried out but it is believed that, whilst in general the subject of TRFs is not fully discussed, most schools do discuss the subject to a certain extent. Some schools, for example FAST helicopters (Shoreham, Robinson R22), CSE (Oxford, Schweizer 269) and Southern Air (Shoreham, Enstrom), all demonstrate the effects of control jams (full non-power pedal also providing some appreciation of TRDF) even though it is not a formal part of the course. It is understood that in some advanced courses, full pedal inputs in the hover are demonstrated to give some impression of yaw rates.

It is recommended that all flying schools at least demonstrate the effects of extreme TR pitch jams to aid diagnosis, and that techniques are explored where it is safe to do so.

7 Awareness

In the civil world, there is very little opportunity for the transfer of experience across the ‘generations’ of aircrew, in contrast to the military environment which involves crew room discussions, pilot’s notes quizzes and general scope for the exchange of anecdotes. Civil pilots tend to come to work, fly and go home. The military also foster interest in the technical aspects of aircraft emergencies through articles in flight safety magazines such as Cockpit (e.g. [14]) and Air Clues. There is not the same incentive in the civil environment to produce such an article (commercial confidentiality, liability and other questions arise) and not the same forum in which to discuss ideas.

It is recommended that such experience be collated by the civil authorities or pilots associations and made readily available to the training organisations.

8 Conclusions

Cross-references to the main text are given in parentheses.

8.1 Simulator training

- Criteria for the validation of training simulators were formulated by the US Federal Aviation Administration in 1994, and are in the process of being formulated in a similar fashion by the Joint Aviation Authorities Committee. There are four standards ranging from Level A to Level D (the highest). The first facilities to be certified to Level C and Level D (of which there is currently only one) were commissioned in 1998. It should be noted that one of the requirements for Level D certification is a continuous vertical field of view of 60° (3.2).
- Nine training simulator facilities responded to a questionnaire aimed at assessing the level of TRF simulation training provided to aircrews and instructors. More than half of the facilities were commissioned in the 1980s, and two thirds employ six degree of freedom motion systems. Two thirds reported some degree of flight data validation over the OFE, but only the three Lynx simulators are likely to have benefited from any form of TRF validation. All of the respondents provide some form of TRF diagnosis and recovery instruction, although this is not a formal part of the teaching course in at least one case. Both TRDFs and TRCFs are covered in some form by most, but it is unclear how realistically they are modelled. In some cases it was stated that the rate of recovery from simulated TRFs is improved dramatically by the training provided, but it remains unclear how successful these recovery techniques may be in the actual aircraft. The highest confidence is

thought to lie with the Lynx simulators due to the techniques having been validated through QinetiQ/WHL flight test and AFS studies (5).

8.2 **Flight training**

- A survey of all helicopter schools was not carried out, but it is believed that, whilst in general the subject of TRFs is not fully discussed, most schools do discuss the subject to a certain extent. Some schools demonstrate the effects of control jams (full non-power pedal also providing some appreciation of TRDF) even though it is not a formal part of the course. It is understood that in some advanced courses, full pedal inputs in the hover are demonstrated to give some impression of yaw rates (6).

9 Recommendations

Cross-references to the main text are given in parentheses.

9.1 **Simulator training**

- The minimum training simulator certification level appropriate for TRF training should be Level C as defined in US Federal Aviation Administration Advisory Circular AC 120-63; the Level D continuous vertical field of view requirement of 60° being likely to restrict many facilities to this standard in any case. Inherent in this is the recommendation that all training simulators are built with motion available in all six degrees of freedom (surge, sway, heave, roll, pitch and yaw), and that the field of view be as representative as possible, particularly with respect to the provision of ground speed visual cues (3.2).
- Replication in a simulator of the actual aircraft field of view, including separate screens to represent chin windows, for example, could conceivably fail to meet the AC 120-63 Level D minimum continuous field of view requirements. It is recommended that the standards authorities revise these requirements, so that replication of the actual aircraft field of view is sufficient for Level D standard (3.2).
- It is recommended that the training providers validate their facilities against flight data over not only the OFE, but also for those areas of the flight envelope likely to be encountered during emergencies, including TRFs wherever possible. This should be carried out for existing facilities, and also for future facilities prior to commissioning. Where flight test data or validated advice cannot be provided, subjective assessment should be carried out against the experience of those who have suffered failures. Where not undertaken already, such experience should be shared within the piloting community, perhaps collated by the civil authorities or pilots associations and made readily available to the training organisations (3.3, 7).
- The recognition of the failure symptoms and the correct crew diagnosis and initial reaction should be the prime aim of training. It cannot be overstated that provision of inappropriate training could exacerbate the problems encountered during emergencies, particularly TRFs, and validation is the only way to reduce such a risk (1).
- Where not already undertaken, it is recommended that validated TRF simulation diagnosis and recovery training is part of normal Service, company and civil authority emergency training policy. Providing awareness of TRFs is one of the aims of this report, and the flying training schools must promulgate this awareness (7).
- Based on a detailed assessment of three facilities, the following additional recommendations are made (4.5):

- Where possible, variation of MR speed should be explored for recovery from TRCFs.
- TRDFs should be demonstrated with both zero run-down time and a short duration rundown time.
- Event replays in real-time or slow time, graphical displays of time histories of aircraft dynamic and control inputs that could be displayed will aid an appreciation of the failure handling.
- Where possible, examples of the sound and vibration associated with TRDFs should be captured or simulated for inclusion in training.

9.2 **Flight training**

- There is evidence that some flying training schools discuss TRFs and demonstrate TRCFs, but they are thought to be in the minority. Although full realism cannot be provided in most cases, it is recommended that all flying schools at least demonstrate the effects of extreme TR pitch jams to aid diagnosis, and that techniques are explored by the students where it is safe to do so (6).

Section 9 Conclusions

Cross-references to the main section conclusions are given in parentheses.

1 Introduction

- A study has been conducted into tail rotor failures (TRFs) and their consequences. The motivation for the study was the overwhelming evidence gathered by the UK Tail Rotor Action Committee (TRAC) that TRFs were occurring at rates much greater than the airworthiness design standards require. This was particularly true for tail rotor (TR) drive systems but also TR control systems, and applied to both civil and military types. The following sub-sections summarise the key conclusions from each phase of the study.

2 The nature and extent of TRFs

2.1 The nature of TRFs

- Different levels of compensation will be required for each of the lost or degraded TR functions, (depending on the phase of TRF management and control and the type of TRF. Primarily, it is the inherent response characteristics of the helicopter that determine the ability to provide the compensation required (Section 2, paragraph 5.1).
- For TRDFs, and TRCFs where the post-failure pitch angle of the TR blades is different from the pre-failure trim position, the immediate effect is a yaw response. The level of initial yaw acceleration will depend on the nature of the failure; the level of yaw rate and attitude build-up will depend on the forward speed. The extent of such excursions and associated disorientation is critical to successful recovery (Section 2, paragraph 5.1).
- The pilot workload during the landing phase is very high, but aligning the aircraft is arguably the most critical task in minimising loss of life and major airframe damage (Section 2, paragraph 5.1).
- Examples of the nature of TRFs, as found during simulator trials on the QinetiQ Bedford Advanced Flight Simulator, are given in the following paragraphs:
- **TRDFs in forward flight**: A TRDF at high speed, with a pilot intervention time (PIT) of 2 seconds, results in transient sideslip that is likely to be beyond the structural limits of the aircraft. In addition, the combined sideslip/roll and reduced collective pitch, applied by the pilot to suppress the yaw transient, causes the main rotor (MR) to be exposed to very high angles of incidence such that the MR speed will exceed the transient limit. The general character of the response was similar for both the hingeless and articulated MR helicopter configurations tested (Section 6, paragraph 6.1).
- **TRDFs in the hover**: With a PIT of 2 seconds there seems to be little that can be done to avoid the spin entry caused by the TRDF unless significant yaw damping can be provided. The ability of the pilot to recover from the initial spin, and avoid entry into an even more severe flat spin by increasing forward speed, is likely to depend on the detailed aerodynamic characteristics of the fuselage and empennage (i.e. type-specific). Their interactions and the functionality of the

Automatic Flight Control System (AFCS) in the pitch and roll channels will also influence the results (Section 6, paragraph 6.1).

- **HP TRCFs**: Recovery from HP TRCFs in both forward flight and in the hover was very difficult. A failure in the hover leads to a rapid build-up in yaw and the chances of recovery without significant damage are low, even from the low hover unless a landing is made positively and rapidly. Attempts to fly out from the high hover are likely to prove very difficult (Section 6, paragraph 6.1).
- **LP TRCFs**: LP TRCFs are similar in some respects to TRDFs, except that the TR continues to provide both yaw stiffness and damping in forward flight and damping in the hover. The response characteristics have the same pattern as for TRDFs, although generally more benign, and it is appropriate to draw similar handling qualities conclusions as for the TRDFs (Section 6, paragraph 6.1).
- **TP TRCFs**: TP TRCFs are very benign compared to TRDFs and the other types of TRCF and in general, satisfactory handling qualities were reported (Section 6, paragraph 6.1).

2.2 **The extent of TRFs**

- A review of the TRAC report revealed some anomalies in the quoted occurrence rates. In the revised statistics, the overall TRF accident rates for the UK fleets covered in the TRAC report were, nevertheless, at least 8 times worse than the UK military requirement of 1 per million flying hours (Section 2, paragraph 5.2).
- The extended database containing 344 occurrences sourced from the UK, US, Canada and New Zealand revealed that the accident rates across the fleets were in the range 9.2 to 15.8 per million flying hours. There is a large variation in the accident rates for heavy and light aircraft due to the operational conditions and roles performed by the different classes. There are considerable variations in the rates by aircraft type, and there is no annual trend to suggest that rates will reach a consistent figure (Section 2, paragraph 5.2).
- <u>The largest causes of TRF are the TR either striking or being struck by an object which, together, account for approximately one half of all TRF occurrences and fatalities, and failure of the TR drive system which accounts for approximately one third of all TRF occurrences and fatalities (Section 2, paragraph 5.2).</u>
- The largest number of TRF occurrences (27%) and fatalities (56%) for any single phase of flight occur during transit. In view of the relative duration spent in the hover, take-off and landing phases, a disproportionately large number of occurrences (51%) are associated with these high torque phases (Section 2, paragraph 5.2).
- The UK Ministry of Defence (MOD) type most subject to failure is the Lynx (combined Service occurrence rate of 33.2 per million flying hours) but Puma (24.0) and Sea King (22.8) also stand out as exceeding the airworthiness design requirements by a dangerous margin. The AH-1 (19.5) and SH-2 (19.3) stand out most for the US Navy and Marine Corps (Section 2, paragraph 5.2).
- Accident definitions, the classifications of causes and the data recorded differ between the relevant authorities. This makes the use of data more difficult and the results less reliable than would have been the case if a common approach were taken (Section 2, paragraph 5.2).

3 Airworthiness design requirements

- Four objectives have been identified in the design requirements for TR drive systems which echo the goals of the current programme (Section 3, paragraph 5).
- A regulatory gap has been identified in the Joint Aviation Requirements JAR-27 and JAR-29 relating to TR control system failures – current designs are neither pushed, by regulation, towards fail-safe solutions through redundancy, nor to higher 'simplex' integrity through detailed design assessments. A two-path solution has been proposed as practicable and appropriate (Section 3, paragraph 5).
- With TRs demonstrably not as reliable as the design standards require, an equally important airworthiness aspect relates to the ability of the aircrew to manage and control the helicopter following a TRF. Handling qualities with a failed TR are severely degraded. Key parameters which affect aircraft handling in such failure conditions include residual yaw stiffness and yaw damping (Section 3, paragraph 5).
- It is not clear what rate of yaw transient defines the safety critical Level 2/3 boundary during TRDFs in the hover (Section 6, paragraph 6.1).

4 Prevention and mitigation of TRFs using HUMS technology

- Based on analysis of the occurrence database, conservative estimates are that 49% of TRFs caused by failure of the TR drive system and 18% of TRFs overall could have been prevented by current Health and Usage Monitoring Systems (HUMS), used as a maintenance aid. In addition, a development of the existing HUMS technology would have prevented or mitigated a further 15% of TRFs caused by failure of the TR drive system, and 5% of TRFs overall (Section 4, paragraph 5).
- The use of current and developed HUMS technologies alone will not bring the occurrence rate to an acceptable level. Other means are required to help avoid hazards, make the TR system less susceptible to damage and maximise the chances of a pilot successfully dealing with a failure that occurs in flight (Section 4, paragraph 5).
- Another technology proposed is a scanning laser tip strike warning system that would draw the pilot's attention to the actual position of an obstacle. The effectiveness of this technology in helicopters is so far unproven, but could have prevented a further 8% of all TRF occurrences (Section 4, paragraph 5).

5 Prevention and mitigation of TRFs using non-HUMS technologies

- TRCF problems can be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch (e.g. as currently used in some types of Spring Bias Unit (SBU)). The fail-safe pitch should function in the event of a control rod disconnection between the pedals and the servo or between the servo and the TR. The simulated TP TRCF cases studied suggest that setting a mid range TR pitch condition on TRCF in forward flight provides benign handling characteristics from which recovery should be made comfortably (Section 5, paragraph 6, Section 6, paragraph 6.2).
- Increasing fin effectiveness off-loads the TR and therefore the severity of a TRF during forward flight. This can be achieved through increasing fin size or through

physical or effective changes to fin camber. A 50% increase in fin size had a marked favourable effect on the failure transient during the simulations. Excessive increase in fixed fin size, however, does have several disadvantages that must be taken into account (Section 5, paragraph 6, Section 6, paragraph 6.2).

- A drag chute has the ability to be retrofitted, requires a relatively small area to produce significant yaw stiffness and does not affect low speed performance. A drag chute would help to control pitch attitude in the event of loss of mass from the tail, help to constrain heading, and can be used in the event of TRCFs that result in both high and low TR thrust conditions. Reduction of the yaw transient, however, is highly dependent upon the drag chute deployment time; the drag chute was ineffective in suppressing the yaw transient with the 2-second deployment time used for the simulations. The increase in drag following deployment of the parachute will reduce the range of the helicopter, and may also result in increased MR head/mast bending, which could have a dramatic effect on MR fatigue life (Section 5, paragraph 6, Section 6, paragraph 6.2).
- A twin TR system could offer many benefits, however, it should be associated with a twin drive shaft system and duplex controls for the maximum benefit to be gained. Quantification of the design, weight and complexity issues associated with duplex and robust simplex drives appears not to have been previously carried out (Section 5, paragraph 6).
- The consequences of transient effects on deployment and failure of the mitigating technologies must be considered. Inadvertent deployment is an issue for all deployable and reversionary devices (Section 5, paragraph 6).
- Minimising the PIT is crucial for survival in all TRF situations. A well designed warning device, which directs the pilot rapidly to the failure recovery, could be effective in reducing the PIT and aiding survival (Section 6, paragraph 6.2).
- Increasing the pitch/roll attitude hold authority within the AFCS can lead to significantly reduced roll and, hence, MR speed transients (Section 6, paragraph 6.2).
- Significant yaw rate damping was found to be required to provide tolerable handling qualities in the hover during the simulations, and off-line tests suggested that such damping levels would be difficult to achieve in reality using devices such as a variable tail boom strake (Section 6, paragraph 6.2).
- HP TRCFs in the hover result in a yaw rate build-up over the failure time. Reducing collective pitch increases the yaw rate, however, reducing MR speed, in conjunction with raising the collective, proved very effective in increasing MR torque and reducing TR thrust, the combination leading to a significant reduction in yaw rate and recovery from the low hover (Section 6, paragraph 6.2).
- From a detailed analysis of 29 example occurrence reports, it is considered that the various prevention and mitigation technologies would have produced a beneficial effect in 90% of all the cases. If the retrofit devices alone are considered the technologies would still have produced a beneficial effect in 79% of all the cases. The technologies providing benefit in most cases were the drag parachute, inflatable fin and twin TR/fan with duplex TR drive. In-line ducted fan solutions and variable camber fin also featured to a lesser extent, and for the TRCF cases, the SBU-type devices were largely beneficial. The sample analysed represents only 20% of the 144 UK occurrences detailed in [10]. However, extrapolation of the analysis to cover all those occurrences indicates that at least 66 of the 78 such cases resulting in TRDF, and 114 overall, could have benefited from the mitigating technologies (Section 5, paragraph 6).

6 Emergency procedures and advice

- The only complete method of determining the applicability of the advice given to aircrews would be to undertake a validation exercise on each aircraft type. The validation exercise must be type-specific because of the variation in possible failure modes, and the basic fuselage stability and control systems characteristics. The validation process must be undertaken against a set of defined criteria, which should be stated with the advice given (Section 7, paragraph 4).
- Ideally, all validation of advice and recovery techniques should aim to achieve Type 1 (full in-flight demonstration of the recovery technique). However, from a practical standpoint, TRDFs can only be demonstrated by piloted simulation and therefore the associated recovery techniques can only achieve Type 2 validation (demonstration using the best available engineering calculations coupled with piloted simulation) (Section 7, paragraph 4).
- The variation in the standard of advice observed would suggest that there is considerable room for improving the level of advice currently given in the Aircrew or Flight Manuals (Section 7, paragraph 4).

7 Training

- Criteria for the validation of training simulators were formulated by the US Federal Aviation Administration in 1994, and are in the process of being formulated in a similar fashion by the Joint Aviation Authorities Committee. There are four standards ranging from Level A to Level D (the highest). The first facilities to be certified to Level C and Level D (of which there is currently only one) were commissioned in 1998. It should be noted that one of the requirements for Level D certification is a continuous vertical field of view of 60° (Section 8, paragraph 8.1).
- Of the 9 training simulator facilities who responded to a questionnaire aimed at assessing the level of TRF simulation training provided to aircrews and instructors, only the three Lynx simulators are likely to have benefited from any form of TRF validation. All of the respondents provide some form of TRF diagnosis and recovery instruction; both TRDFs and TRCFs are covered in some form by most, but it is unclear how realistically they are modelled and how successful these recovery techniques may be in the actual aircraft (Section 8, paragraph 8.1).
- It is believed that most helicopter schools do discuss the subject of TRFs to a certain extent, and some schools demonstrate the effects of control jams. It is understood that in some advanced courses, full pedal inputs in the hover are demonstrated to give some impression of yaw rates (Section 8, paragraph 8.2).

Section 10 Recommendations

Cross-references to the main section recommendations are given in parentheses.

1 The nature and extent of TRFs

- It is recommended that the relevant authorities co-operate to standardise accident and incident classifications, and the details recorded in occurrence reports world-wide (Section 2, paragraph 6).

2 Airworthiness design requirements

- It is recommended that the Joint Aviation Requirements (JARs) be amended to provide a two-path solution to closing the regulatory gap. In particular the JAR 29.671 should be revised to require the two-path approach as described in 3.5. The same advisory material as provided for JAR29.547, describing how a design assessment is performed, should be used (Section 3, paragraph 6).
- It is recommended that the ADS-33D failure transient limits, collective to yaw requirements and sideslip excursion limitations are used as a means of quantification in the failure modes and effects analysis, as part of the two-path solution (Section 3, paragraph 6).
- Manufacturers should be required to analyse the effect of TRFs and, where these effects are significant, provide at least Type 2 validated aircrew advice. Where such advice is not provided, it is recommended that advisory operational restrictions be provided (similar to the H-V diagram for engine failures). Such restrictions could also be realised through the inclusion of a reference to flight control/handling characteristics following tail rotor failures (TRFs) in Sub-Part B of JAR-27 and JAR-29 (Section 3, paragraph 6).
- Handling qualities with a failed tail rotor (TR) are severely degraded. It is recommended that the airworthiness requirement authorities establish the residual yaw stiffness and damping which should be available after TRFs. It is recommended that manufacturers explore the potential of technologies which exploit improved stiffness and damping to mitigate against TRFs by providing improved handling (Section 3, paragraph 6).
- As far as the ability of the pilot to recover from a TR drive failure (TRDF) at typical cruising speeds and altitudes is concerned, the simulator trials results suggest that with a pilot intervention time (PIT) of 2 seconds the following should apply (Section 6, paragraph 6.1):
  - For ADS-33D Level 2 (adequate) handling qualities, the directional stiffness should be such that the initial transient sideslip peak is less than the Operational Flight Envelope (OFE) limit, or 30° whichever is the smaller.
  - Considering the flight critical nature of the TR function, it is suggested that the handling boundary of most relevance for both low level and up-and-away flight is that between Level 3 and Level 4. Although by definition Level 3 (controllability compromised) handling qualities are unacceptable, it is recommended that for this Level, the directional stiffness should be such that the initial sideslip peak is less than that causing structural limit loads to be reached or 60° whichever is the smaller.

  - In terms of transient roll response, the combined dihedral effect (which, depending on the type, may be either advantageous or adverse at the transient sideslip peak) and attitude hold function in the Automatic Flight Control System (AFCS) should be such as to contain the roll transient to less than 30° for Level 3 handling qualities and 10° for Level 2.
  - There should be no requirement for engine shutdown to be part of the time critical pilot actions.
- Further work should be carried out to firmly establish what rate of yaw transient defines the safety critical Level 2/3 boundary during TRDFs in the hover (Section 6, paragraph 6.1).

3 Prevention and mitigation of TRFs using HUMS technology

- Where Health and Usage Monitoring Systems (HUMS) are currently fitted, the fault detection capability of the HUMS should be fully exploited, and operators should develop effective procedures for use in conjunction with the system so that HUMS information is acted on in a correct and timely manner (Section 4, paragraph 6).
- <u>The fitting of appropriately designed HUMS, focussed on (but not limited to) monitoring TR drive system failure is strongly recommended (Section 4, paragraph 6).</u>
- <u>Action should be taken to further define the HUMS required for specific types or categories of helicopter. This should take into account the specific failure types, the handling qualities of the aircraft post-failure and economic factors (Section 4, paragraph 6).</u>
- Automated tools to assist in the examination of data collected by the current HUMS, and in the identification of potential fault-related trends should be improved (Section 4, paragraph 6).
- In the longer term consideration should be given to providing an intelligent cockpit warning system that prioritises warnings, presents immediate actions, guides the pilot through a sequence of steps, and makes supporting information available (Section 4, paragraph 6).
- Further work should be conducted to define an approach for the presentation of in-flight information, following on from the recommendations of the 1998/9 HHMAG (Helicopter Health Monitoring Advisory Group) Working Group on flight deck health monitoring indications (Section 4, paragraph 6).
- Work should be undertaken to evaluate the merits of the new technology for rotor tip strike warning to reduce occurrences where the TR hits an obstacle (Section 4, paragraph 6).

4 Prevention and mitigation of TRFs using non-HUMS technologies

- <u>TR control failure (TRCF) problems should be addressed by improved design of the control circuit, in particular, the incorporation of a fail-safe pitch (e.g. as currently used in some types of Spring Bias Unit (SBU)). Further type-specific studies should be carried out to determine the mechanisms and settings required, and to investigate the transient behaviour on TRCF and activation of the device (Section 5, paragraph 6, Section 6, paragraph 6.2).</u>

- Main rotor (MR) speed control (increase and decrease from trim) should be provided to the aircrew to assist in recovery from TRCFs in the hover (Section 6, paragraph 6.2).
- Deployable devices, such as an inflatable fin and drag parachute, should be investigated for retrofit on existing types and incorporated in the design of future types to provide additional yaw stiffness in the event of TRF (Section 6, paragraph 6.2).
- It is recommended that further work be carried out to examine the feasibility of duplex and robust simplex drive systems (Section 5, paragraph 7).
- A well designed warning device, which directs the pilot rapidly to the failure recovery, should be incorporated into cockpits to reduce the PIT and increase the chances of recovery (Section 6, paragraph 6.2).
- It is recommended that studies be conducted to examine how best to achieve increased fin effectiveness without unduly compromising vehicle performance (Section 5, paragraph 6).
- Control systems should be provided with variable authority, attitude command/ attitude hold response types (or better), to enable reduction of the pitch and roll transients resulting from TRF, particularly at high speed (Section 6, paragraph 6.2).

5 Emergency procedures and advice

- It is strongly recommended that type-specific piloted simulation and, where possible, flight test programmes are put in place to develop advice validated to a minimum of Type 2 (demonstration using the best available engineering calculations coupled with piloted simulation) for TRFs in general, and Type 1 (full in-flight demonstration of the recovery technique) for TRCFs (Section 7, paragraph 5).
- The variation in the standard of advice currently given in Aircrew or Flight Manuals (AMs/FMs) suggests that there is considerable room for improvement (Section 7, paragraph 5). In particular, it is recommended that:
  - The advice should make clear whether the use of a power and speed combination is appropriate or not during recovery from TRDFs.
  - The advice should contain information on techniques required to control the descent.
  - The loss of tail pylon/TR components should be identified as a source of possible aircraft pitch control problems.
  - Unusual vibrations emanating from the TR area of the helicopter should be identified as being indicative of a possible TR problem and pilots should be advised to set up a minimum power condition if in forward flight, or to land and shut down for technical investigation if in the hover.
  - Unusual pedal positions should be identified as a possible impending TRF condition. The advice should recommend setting up a minimum power condition if in forward flight, or to land and shut down for technical investigation if in the hover.
  - The effects of a TR control circuit disconnect on the TR pitch condition should be identified.

    - Subject to validation, and where appropriate to the type (i.e. where the pilot has the ability to control rotor speed) the benefit of varying MR speed in the hover following a TRCF should be reflected in the advice.
- Simulation of the TRDF conditions should be undertaken using high fidelity flight mechanics models to ensure any recommendations to seek a power and speed combination are justified (Section 7, paragraph 5).
- There should be a requirement for the manufacturers to identify the possible failure modes of the TR control circuit, and the impact of TRFs on the anti-torque moment supplied by the TR so that appropriate advice can be generated. It is also recommended that manufacturers be mandated to provide validated advice for all types (Section 7, paragraph 5).

6 Training

- The minimum training simulator certification level appropriate for TRF training should be Level C as defined in US Federal Aviation Administration Advisory Circular AC 120-63. Inherent in this is the recommendation that all training simulators are built with motion available in all six degrees of freedom (surge, sway, heave, roll, pitch and yaw), and that the field of view be as representative as possible, particularly with respect to the provision of ground speed visual cues (Section 8, paragraph 9.1).
- It is recommended that the standards authorities revise the AC 120-63 Level D minimum continuous field of view requirements, so that replication of the actual aircraft field of view is sufficient for Level D standard (Section 8, paragraph 9.1).
- It is recommended that the training providers validate their facilities against flight data over not only the OFE, but also for those areas of the flight envelope likely to be encountered during emergencies, including TRFs wherever possible. This should be carried out for existing facilities, and also for future facilities prior to commissioning. Where flight test data or validated advice cannot be provided, subjective assessment should be carried out against the experience of those who have suffered failures. Where not undertaken already, such experience should be shared within the piloting community, perhaps collated by the civil authorities or pilots associations and made readily available to the training organisations (Section 8, paragraph 9.1).
- The recognition of the failure symptoms and the correct crew diagnosis and initial reaction should be the prime aim of training. It cannot be overstated that provision of inappropriate training could exacerbate the problems encountered during emergencies, particularly TRFs, and validation is the only way to reduce such a risk (Section 8, paragraph 9.1).
- Where not already undertaken, it is recommended that validated TRF simulation diagnosis and recovery training is part of normal Service, company and civil authority emergency training policy. Providing awareness of TRFs is one of the aims of this report, and the flying training schools must promulgate this awareness (Section 8, paragraph 9.1).
- Based on a detailed assessment of three facilities, the following additional recommendations are made (Section 8, paragraph 9.1):
    - Where possible, variation of MR speed should be explored for recovery from TRCFs.

- TRDFs should be demonstrated with both zero run-down time and a short duration rundown time.
- Event replays in real-time or slow time, graphical displays of time histories of aircraft dynamic and control inputs that could be displayed will aid an appreciation of the failure handling.
- Where possible, examples of the sound and vibration associated with TRDFs should be captured or simulated for inclusion in training.

- Although full realism cannot be provided in most cases, it is recommended that all flying schools at least demonstrate the effects of extreme TR pitch jams to aid diagnosis, and that techniques are explored by the students where it is safe to do so (Section 8, paragraph 9.2).

Section 11 Acknowledgements

In addition to the authorities acknowledged in Table 2-6, grateful thanks are also due to the US Navy and Marine Corps Safety Centers and the US Coast Guard HQ, for their provision of tail rotor failure occurrence reports and/or statistics for analysis, and permission to publish summary statistics.

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Section 14 List of symbols

a_0	Rotor lift curve slope
a_{Fin}	Fin lift curve slope
g	Acceleration due to gravity
$\dot{h}$	Height rate
l_t	Distance between main and tail rotor hubs
p	Roll rate
r	Yaw rate
C_{do}	Drag coefficient
D_{chute}	Parachute drag
L	Lift
N	Yaw moment
N_R	Main rotor speed
R	Rotor radius
S	Rotor disc area
S_F	Fin area
S_P	Parachute frontal area
V	Forward velocity
V_{NO}	Normal operating speed
V_Y	Best rate of climb speed
β	Sideslip angle
μ	Advance ratio
ρ_0	Air density at sea level International Standard Atmosphere
σ	Density ratio
$\varnothing_1$	Initial peak magnitude in roll response
ψ_β	Phase angle
Ω	Rotor speed

Section 15 List of abbreviations

AAC	Army Air Corps (UK)
AAIB	Air Accidents Investigation Branch (UK)
ACAH	Attitude command, attitude hold
ACJ	Advisory Circular Joint
ADR	Accident Data Recorder
AEO	Air Engineering Officer
AFCS	Automatic Flight Control System
AFS	Advanced Flight Simulator
AGARD	Advisory Group for Aerospace Research and Development (NATO)
AGL	Above ground level
AM	Aircrew Manual
AMSL	Above mean sea level
AOB	Angle of bank
ATC	Air Traffic Control
AUW	All Up Weight
BCAR	British Civil Airworthiness Requirements
BUCS	Back-Up Control System
CAA	Civil Aviation Authority (UK)
CVR	Cockpit Voice Recorder
DERA	Defence Evaluation and Research Agency (UK)
DOF	Degree of freedom
EHQR	Equivalent Handling Qualities Rating
FBL	Fly-by-light
FBW	Fly-by-wire
FDR	Flight Data Recorder
FM	Flight Manual
FOD	Foreign Object Damage
FRR	Failure/recovery rating
HHMAG	Helicopter Health Monitoring Advisory Group
HLO	Helicopter Landing Officer

HP	High pitch
HQR	Handling Qualities Rating
HUMS	Health and Usage Monitoring System
ICQ	In-cockpit questionnaire
IDS	Inclined Driveshaft
IFS	Inspectorate of Flight Safety (RAF)
IHUMS	Integrated Health and Usage Monitoring System
IPT	Integrated Project Team
JAR	Joint Aviation Requirements
LatCyc	Lateral cyclic
LP	Low pitch
MOD	Ministry of Defence (UK)
MORS	Mandatory Occurrence Reporting System (CAA)
MR	Main rotor
MYR	Modified yaw response
NASA	National Aeronautics and Space Administration (US)
NFG	Negative Force Gradient
nm	Nautical mile
NTSB	National Transportation Safety Board (US)
OFE	Operational Flight Envelope
OMP	Outline Management Plan
PIT	Pilot intervention time
RAF	Royal Air Force (UK)
RAFHS	Royal Air Force Handling Squadron (UK)
RC	Rate command
RN	Royal Navy (UK)
RNAS	Royal Naval Air Station (UK)
rpm	Revolutions per minute
SAS	Scandinavian Airline Services
SBU	Spring Bias Unit
SAES-S	Smiths Aerospace Electronic Systems - Southampton (part of the Smiths Group)
SHSS	Steady Heading Sideslip

SSL	Speed Select Lever
TO1C	Turn on one cyclic
TP	Trim pitch
TR	Tail rotor
TRAC	Tail Rotor Action Committee
TRCF	Tail rotor control failure
TRDF	Tail rotor drive failure
TRF	Tail rotor failure
TRGB	Tail rotor gearbox
TTR	Twin tail rotor
USCG	United States Coast Guard
USMC	United States Marine Corps
USN	United States Navy
WHL	Westland Helicopters Limited (part of AgustaWestland)

Appendix A Detailed assessment of selected tail rotor failure occurrences

1 Introduction

This appendix presents a detailed description of 31 TR-related occurrences, categorised according to the primary failure mode. They have been selected to give examples of at least one of each of the main failure cause categories identified in Section 2 of this report. TRDFs are the largest single cause of fatalities and account for a significant proportion of all occurrences. Because of this, and the relevance of current HUMS for transmission health monitoring, the TRDFs have been examined in further detail. TRCFs are also relevant to current HUMS and are examined in further detail. The material for the HUMS prevention and mitigating technology analysis was taken from [10] as reported on in Section 4 and the additional material for the non-HUMS prevention and mitigating technologies was taken from [18] as reported on in Section 5.

The cause categories analysed were as follows:

- The TR hit an obstacle
- An object hit the TR
- Tail/boom structural failure
- TRDF with the folowing sub-categories:
  - failure of the TR gearbox mounting
  - failure of the TR drive shaft
  - failure of a TR drive shaft spline coupling
  - failure of a TR drive shaft Thomas coupling
  - failure of a TR drive shaft tail fold disconnect coupling
  - failure of a TR drive shaft hanger bearing
  - failure of an intermediate or TR gearbox
  - failure of TR hub components
  - TR blade failure
- TRCF with the following sub-categories:
  - TR pitch control system seized/jammed
  - TR pitch change mechanism failure
- Loss of TR effectiveness

More than one occurrence is presented in some of the above failure categories. The actual occurrences included have, in many cases, been selected on the basis of the availability of detailed information on the nature of the occurrence, and the findings of the subsequent investigation. The prime sources of detailed information on the 31 selected occurrences were Air Accidents Investigation Branch (AAIB) accident reports and bulletins, and MOD accident reports. Only turbine-powered helicopter occurrences have been selected; however they include both small and large helicopters (as defined for Joint Aviation Requirements JAR-27 [2] and JAR-29 [3]). Some entries were classed as incidents and some as accidents.

The following information is presented for each occurrence:

- Key occurrence details;
- a history of the flight;
- the findings of the subsequent accident investigation;
- an analysis of the occurrence with regards to the possible impact of HUMS diagnostic techniques; and
- the applicability of mitigating technologies.

The occurrence analysis is presented as follows:

- What warning information was or could be made available prior to the failure? This warning would either prevent the flight on which the occurrence took place or, if an in-flight warning was possible, enable the pilot to terminate the flight before the failure occurred.
- What diagnostic information was or could be made available post-failure? This information is used by the aircrew to diagnose the nature of the failure so that they can take the most appropriate recovery action.
- What actions were or might have been taken based on the warning or diagnostic information?
- What were the effects of these actions?

The analysis of the possible impact of HUMS considered both the capabilities provided by current systems and capabilities that could be provided by development of these systems, or the implementation of new monitoring technologies. For example, current HUM systems could only provide an on-ground warning prior to the flight on which the occurrence took place. However HUMS could be developed to provide warning and diagnostic information to pilots during a flight. The analysis was intended to indicate the possible benefits, and hence justification, for any such developments.

It is recognised that poor maintenance/inspection practices may have been a contributory factor in some of the occurrences described, therefore some of them may have been prevented by improved maintenance practices. However, the analysis of the potential impact of HUMS was based on the fact that they did occur and, irrespective of the causes, HUMS would have been able to prevent some of them. The benefits from HUMS are not just limited to an ability to detect failures resulting from design or material defects in components, but include an ability to detect failures resulting from abnormal use and poor maintenance of components.

The key to the non-HUMS prevention and mitigating technologies is shown in Table A-1. Their applicability is shown by shading of the appropriate cell in the table; black shading indicates that the technology was/would have been of use, and grey shading indicates that the technology may have been of use. Occurrence No. 7 and occurrence No. 8 were not assessed for mitigating technologies since they resulted from structural failure rather than from failure of the drive or control systems.

Table A-1 Key to non-HUMS prevention and mitigating technologies

Abbreviation	Technology
DC	Drag chute
IF	Inflatable fin
SBU	Spring Bias Unit/Negative Force Gradient spring
FBW	Fly-by-wire/fly-by-light
SLP	Secondary load paths
HYD	Duplex hydraulic systems
SRU	Spring return unit
BUCS	Back-Up Control System
AFCS	AFCS systems with adjustable control authority
ECS	Engine chop switch/throttles
TTDD	Combined twin TR/fan and duplex conventional TR drive systems
DF	Novel (in-line) simplex ducted fan system
VCF	Variable camber fin
CNR	Controllable MR speed
RSDS	Robust simplex TR drive system

2 TR hit an obstacle

2.1 Occurrence number 1 (the TR hit an obstacle)

2.1.1 **Key details**: see Table A-2:

Table A-2 Occurrence No. 1 (the TR hit an obstacle) - key details

Aircraft type/registration:	Sikorsky S-61N G-BEWL
Date and time:	25 July 1990 at 0944 hours
Location:	Brent Spar, East Shetland Basin
Operator/type of flight:	Public transport
Injuries:	6 fatalities
Nature of damage:	Helicopter destroyed
Information source:	AAIB Aircraft Accident Report No 2/91

2.1.2 **History of the flight**: The helicopter was on a flight from Sumburgh to the ‘Polycastle’ accommodation vessel located alongside Brent Alpha, and then on to Brent Spar. It lifted off from the ‘Polycastle’ at 0940 hours and established radio contact with Brent Spar. The Helicopter Landing Officer (HLO) gave landing clearance to the crew. The helicopter flew along the port side of a tanker that was moored to the Spar in what appeared to be a normal manner, and became established in a hover adjacent to and about 50 feet above the level of the helideck.

The helicopter then moved to the right, crossing the edge of the deck, and appeared to drift slightly rearwards while yawing to the left. Some of the passengers on board the helicopter became concerned at its position in relation to the installation, feeling that they were abnormally close to the crane and misplaced from the normal landing position. Some of them reported the tail of the helicopter swinging to the right just before impact and it became apparent to eyewitnesses on the Spar that there was an imminent danger of the tail of the helicopter striking part of the crane structure. The HLO also observed the helicopter's hazardous position but before he was able to radio a warning to the crew, there was the sound of TR blades striking part of the crane structure. The helicopter thereafter yawed to the right through about 150° and crashed onto the deck whilst still yawing.

The helicopter momentarily came to rest on the edge of the helideck however, before the passengers and crew could escape, it fell over the edge of the deck and plunged into the sea.

2.1.3 **Findings of the accident investigation**: Weather conditions at the time of the occurrence were adequate for visual contact flying but the horizon was indistinct and there was hardly any wind. Visual cues used routinely by the handling pilot may have led him to position the helicopter closer to the main obstruction before he transferred his attention to the aiming circle, which was displaced from the centre of the deck in order to ensure sufficient clearance. In order to retain sufficient visual reference it is likely that the handling pilot inadvertently moved rearwards as he descended and thus unwittingly towards the obstacle.

The helicopter was seen to move obliquely across the deck until the TR struck the crane 'A' frame. Some passengers and observers became aware that it was in a hazardous position prior to the strike. The HLO, although momentarily aware of the helicopter's hazardous positioning, had hardly any time in which to radio a warning to the crew.

The occurrence happened when the handling pilot allowed the helicopter's TR to contact a hand rail surrounding the 'A' frame of the Brent Spar crane which resulted in the helicopter crashing onto the helideck before falling into the sea and sinking.

The following causal factors were identified:

- Negligible wind offered freedom of choice in the direction of approach but required careful handling of the power available and consideration of any rejected landing profile. An indeterminate horizon made attitude control of the helicopter more difficult whilst it was hovering more than the normal 10 foot wheel height above a relatively small structure.
- The commander's choice of approach was inexplicable given the number of more favourable options open to him but it may have been influenced by his previous experiences of approaching Brent Spar in strong wind conditions.
- Orientation of the rotating helideck when a vessel was moored to Brent Spar meant that the major obstacle would often be positioned behind a helicopter which was landing into wind. Pilots were therefore not unused to this situation and the commander may have accepted the constraint it placed upon the direction of approach.

The safety recommendations made by the AAIB included the following:

- It is recommended that methods of ensuring greater security for the TR whether by revised helideck markings, visual position indicators or proximity warning devices be examined.

2.1.4 **Analysis**: See Table A-3.

Table A-3 Occurrence No. 1 (the tail hit an obstacle) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">TR hit a crane on the oil platform</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Landing</td></tr>
<tr><td>Consequence:</td><td colspan="5">Fatal accident</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">None</td></tr>
<tr><td>Action:</td><td colspan="5">None</td></tr>
<tr><td>Effect:</td><td colspan="5">None</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">None possible with HUMS. However, a TR tip strike warning system could have alerted the pilot to the threat to the TR.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Post TR strike diagnostic information would have been of no value.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">For a tip strike warning system, any information should prompt the pilot to rapidly take action to move the TR away from the obstacle.</td></tr>
<tr><td>Effect:</td><td colspan="5">HUMS could not have prevented this occurrence, however a TR tip strike warning system may have prevented the occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">There would have been possible benefits from a ducted fan or twin TR system solutions assuming in both cases that the impact with the crane did not collapse the fan duct or affect the secondary TR system. A robust TRDS would have absorbed the shock impact and allowed drive to be recovered but overall recovery would have depended on the damage sustained by the TR itself. There would not have been time to make use of deployable devices.</td></tr>
</table>

3 An object hit the TR

3.1 Occurrence No. 2 (an object hit the TR)

3.1.1 **Key details**: see Table A-4:

Table A-4 Occurrence No. 2 (an object hit the TR) - key details

Aircraft type/registration:	AS332L Super Puma (Tiger) G-TIGK
Date and time:	19 January 1995 at about 1240 hours
Location:	Near the Brae 'A' oil production platform
Operator/type of flight:	Public transport
Injuries:	Minor/none
Nature of damage:	Helicopter damaged beyond economic repair
Information source:	AAIB Aircraft Accident Report No 2/97

3.1.2 **History of the flight**: The helicopter was on a flight from Aberdeen to the Brae 'A' oil production platform, stopping first at the East Brae platform. The helicopter took off at 1138 hours and climbed to 7000 feet AMSL.

At about 1236 hours, whilst initiating the normal let down to the East Brae platform and as they passed through a patch of cloud at about 3,000 feet above mean sea level (AMSL), there was a 'bang' accompanied by a 'flash' and the helicopter began to vibrate severely. Assuming an immediate need to ditch, the first officer initiated an autorotative descent and transmitted a MAYDAY call, stating that they had been struck by lightning, had severe vibration and were going to ditch.

As the helicopter descended through 1,500 feet AMSL both pilots realised that, although the helicopter was still vibrating severely, it was responding normally to the controls. They therefore decided to level off and to try to reach the Brae 'A' oil platform, the nearest diversion. The first officer, as the handling pilot, was unsure as to whether the apparent directional stability of the helicopter was being maintained by the TR or by the 'weathercock' effect of the airspeed, so he gently deflected the yaw pedals to see if there was a response. He had just commented to the commander that everything seemed to be in order when there was a 'crack' and the helicopter gave a violent lurch to the left, rolled right and pitched-down steeply.

Realising that a ditching was now imminent, the first officer transmitted another MAYDAY informing Brae of his decision to ditch and carried out the TRDF checks, which included shutting down the engines in order to contain the yaw, and then arming and inflating the floats. The first officer accomplished a gentle touchdown on the sea, despite six to seven metre waves and a 30 knot wind. At 1242 hours the commander made an RT transmission to say that they had alighted safely. All passengers and crew boarded a heliraft and awaited rescue. The helicopter remained afloat for some three hours and thirty minutes.

3.1.3 **Findings of the accident investigation**: One main rotor (MR) blade and one TR blade had suffered high energy lightning strike damage, however the MR continued to operate satisfactorily.

The 'White' TR blade was sufficiently damaged by the lightning strike to induce severe vibration which later caused the complete detachment of the TR, associated gearbox and pitch servo assembly due to cyclic overstressing of the gearbox attachments within some 3.5 minutes of the strike.

The detached mass of the damaged TR, gearbox and pitch servo was fortuitously restrained from complete separation from the tail boom pylon by two of the four hydraulic pipes connected to the pitch servo, which had held it suspended alongside the right side of the pylon, allowing retention of effective helicopter longitudinal pitch control until the ditching had been successfully completed.

After the lighting strike and prior to the TR gearbox separation, the commander faced the decision whether to alight on the sea beside the platform, or whether to attempt a landing on the platform. Historically, ditchings have resulted in helicopters rolling over in the sea, sometimes with a consequent high risk of loss of life. There is therefore, understandably, reluctance on the part of operating crews to ditch voluntarily. However, the degree of vibration produced by a TR imbalance can be so severe that it may be only a short time before the TR assembly and associated gearbox detaches from the helicopter.

The dilemma facing a commander, in such a situation, is therefore whether to ditch and risk loss of life, or to attempt a landing on a platform, hoping that the TR and gearbox will not detach whilst the helicopter is approaching the helideck as a result of the added stresses induced by the necessary changes in torque. The consequences of such an occurrence could be catastrophic due to the accompanying loss of yaw and pitch control. The considerations that have to be taken into account by a commander when severe TR vibration is experienced include the weather, particularly the sea state, the controllability of the helicopter, the size and proximity of the platform, in addition to the time available to make his decision.

Following this accident, there was much discussion on whether a standard procedure should be recommended to crews to adopt in the event of such an emergency. However, bearing in mind the different types of emergency that crews could experience and the varying aspects detailed above, it was concluded that the final course of action must be left to the commander.

3.1.4 **Analysis**: see Table A-5:

Table A-5 Occurrence No. 2 (an object hit the TR) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">TR struck by lightning</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Initiating descent</td></tr>
<tr><td>Consequence:</td><td colspan="5">Ditching</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Some control inputs were required to diagnose the initial status of the TR drive after the lightning strike; there was a correct diagnosis of the subsequent loss of TR drive.</td></tr>
<tr><td>Action:</td><td colspan="5">Correct actions were taken, culminating in autorotation and ditching.</td></tr>
<tr><td>Effect:</td><td colspan="5">Successful ditching</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Immediately after the lightning strike (assuming the sensors were still operational): TR rotational speed monitoring could have indicated that the TR was still rotating correctly. An on-demand vibration check or continuous rotor vibration monitor could have provided some indication of the severity of the damage, and whether the situation was deteriorating. After the loss of the TR: It is assumed that any HUMS sensors would have been destroyed therefore no indication could be given.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">Any HUMS information may have prompted the pilot to initiate an earlier controlled descent and ditching.</td></tr>
<tr><td>Effect:</td><td colspan="5">The outcome of the occurrence (a successful ditching) would have been the same.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">It is possible that several of the technologies discussed in this report could have helped the pilots in the situation described above. If the TR had been unloaded during the cruise using a variable cambered fin, the out of balance forces on the lightly loaded rotor would have generated less severe vibration, reducing the fatigue damage. A ducted rotor on the other hand would have offered protection. Following the lightning strike on the conventional TR and the increased level of vibration, an inflatable fin would have produced additional yaw stiffness in the event of loss of TR thrust. However, fuselage pitching down effects due to loss of TR hub and gearbox would not have been catered for. The drag chute on the other hand would have stabilised the helicopter in both pitch and yaw following the structural failure of the gearbox attachment points and would have possibly enabled the helicopter to carry on flying straight and level at minimum power speed. Circumstances might still have dictated that the helicopter had to be ditched. A twin TR system solution could have also offered benefits if only one rotor had been damaged and could possibly have enabled a safe landing to be achieved on an oil platform helideck.</td></tr>
</table>

3.2 **Occurrence No. 3 (an object hit the TR)**

3.2.1 **Key details**: see Table A-6:

Table A-6 Occurrence No. 3 (an object hit the TR) - key details

Aircraft type/registration:	AS 350B Squirrel (Ecureuil) G-PLMA
Date and time:	5 May 1995 at 2015 hours
Location:	Near Lochgilphead, Argyll, Scotland
Operator/type of flight:	Underslung load work
Injuries:	1 fatality
Nature of damage:	Helicopter destroyed
Information source:	AAIB Aircraft Accident Report No 4/96

3.2.2 **History of the flight**: The helicopter was involved in the aerial transfer of farmed salmon in Scotland. The pilot was transiting at low level over a sea loch with a sling and hook slung below the helicopter.

One eyewitness saw the helicopter obviously out of control near the shore of the loch. The helicopter was yawing rapidly to the left and right without completing a revolution, and at the same time rolling and pitching. A long black object flew off the helicopter and it then spun around through at least two complete revolutions without losing height. When the spinning stopped, the helicopter dropped nose first to the ground. Another eyewitness saw the helicopter climb and then appear to go out of control in extreme attitudes. A few seconds later what was taken to be the TR detached before the helicopter descended to the ground in a nose-down attitude. The helicopter was seen to crash on the shore of the loch.

3.2.3 **Findings of the accident investigation**: The end of the sling probably contacted the surface of the loch and rebounded into the TR causing separation of the tip of one TR blade. The severe out of balance forces on the TR then caused the separation of the TR gearbox from the tail boom.

The occurrence was brought about by a series of events but there can be little doubt that the event which made it inevitable was separation of the TR gearbox. Once the gearbox broke away, there was no TR force with which to counteract the torque of the MR transmission system and the helicopter would have begun to spin around its MR. The only way to contain this situation is to reduce engine power and execute a forced landing. That this was attempted is fully consistent with all the evidence available.

It was apparent that the tail drive system had operated briefly with the TR gearbox displaced from its normal position while the TR had been rotating at high speed. Relative movement between the gearbox and the structure would have produced uncommanded changes in blade pitch angles because of the pitch control rod geometry. This in turn would have caused the uncontrolled yawing and rolling reported by many witnesses. During this phase the control difficulties were probably so severe that the commander was unable to attempt any form of ‘controlled’ crash landing until the TR had broken free from the tail boom.

Unfortunately when the TR had separated, the helicopter’s height was probably too great to use MR inertia to cushion a vertical landing and too little for effecting a run-on landing, which depends for its success on forward airspeed and a reasonably flat surface (i.e. the helicopter was within the avoid curve). Consequently, a very hard landing in an unusual attitude was unavoidable.

3.2.4 **Analysis**: see Table A-7:

Table A-7 Occurrence No. 3 (an object hit the TR) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">TR hit by sling and hook</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Low level flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Fatal occurrence</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Unknown</td></tr>
<tr><td>Action:</td><td colspan="5">Pilot was unable to take action to prevent the occurrence.</td></tr>
<tr><td>Effect:</td><td colspan="5">Helicopter crashed</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The TR sensors would have been destroyed, therefore no diagnosis would be possible.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">If any information had been available this should have prompted the pilot to take action appropriate to the flight regime (e.g. perform an engine-off landing), however the pilot would have be unable to respond.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS could not have affected the outcome of the occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">It is unclear whether the forward speed was high enough for a variable camber fin to have provided assistance. A suitably sized drag chute could have reduced yaw rate and helped control the pitch attitude, an inflatable fin would have also had some benefit in reducing yaw rate but would not have aided attitude control. A ducted fan might have avoided the damage to the blades and the twin TR system would have provided redundancy assuming the second system remained intact.</td></tr>
</table>

3.3 Occurrence No. 4 (an object hit the TR)

3.3.1 **Key details**: see Table A-8:

Table A-8 Occurrence No. 4 (an object hit the TR) - key details

Aircraft type/registration:	AS355-F2 Ecureuil II G-BOOV
Date and time:	6 January 1993 at 1608 hours
Location:	Liverpool Airport, Merseyside
Operator/type of flight:	Police helicopter
Injuries:	None
Nature of damage:	Helicopter damaged
Information source:	AAIB Bulletin No 5/93

3.3.2 **History of the flight**: The police helicopter had been airborne for around 55 minutes on its first flight of the day. Whilst transiting towards Liverpool City at about 500 feet AGL and an airspeed of around 120 knots the vibration began to increase and the aircraft wallowed, followed almost immediately by a loud bang.

The pilot immediately reduced speed and power. He noted that instrument readings appeared normal, but found that yaw pedal inputs produced no response and declared an emergency. He elected to return to Liverpool Airport as it was only about 3 nm away. After flying past the Liverpool Airport control tower the pilot was informed that the TR was stationary. He shut down the No 2 engine and made a shallow approach parallel to a runway, intending to land on a grassed area to the north of the runway.

As the aircraft slowed to around 30 knots at 50 feet agl, it began to yaw excessively to the left. The No 1 engine throttle was retarded, correcting the yaw, but with the aircraft now heading for the asphalt runway. As collective was increased to cushion the touchdown on the runway, the helicopter began to yaw to the right and in an attempt to control this the pilot allowed it to touch down in a tail down attitude. The contact on the rear end of the skids caused the aircraft to bounce and make a second touchdown in a nose-down attitude, before sliding on the skids to a stop. The helicopter came to a halt upright and around 50 metres from the initial touchdown point.

3.3.3 **Findings of the accident investigation**: It was rapidly apparent that part of the right engine bay door was missing, that a TR strike had occurred and the TR drive system had severed.

Inspection showed that the lower aft part of the right engine bay door, comprising approximately 70% of the door and including the two catches and the restraining cable and strut, was missing. One blade of the TR was severely damaged, but intact, in a manner consistent with a rotational strike of the leading edge with a foreign object. The TR drive shaft had severed in the tunnel between the engines, consistent with the effects of torsion overload due to excessive TR drag. Other damage consisted of a small dent in the lower surface of one MR blade at a radius of 1 metre from the MR hub and localised scratching and denting of the tail boom and fin leading edge.

The evidence was consistent with the unlatched door, having lifted in the airflow, suffering progressive structural failure due to overheating in the engine exhaust efflux combined with airflow buffeting. This caused parts of the door to detach and strike a main and TR blade, applying sufficient shock drag loading to the TR to fail the drive shaft.

The AAIB made the following safety recommendation:

- It is recommended that the CAA require, for UK registered AS350 and AS355 helicopters, the fitment of a system to provide unmistakable cockpit indication to the pilot of improperly latched engine or MGB bay doors.

3.3.4 **Analysis**: see Table A-9:

Table A-9 Occurrence No. 4 (an object hit the TR) - analysis

<table>
<tr><th colspan="6">Occurrence information</th></tr>
<tr><td>Failure mode:</td><td colspan="5">TR hit by part of the engine bay door</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Helicopter damaged</td></tr>
<tr><th colspan="6">Pilot information and response</th></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">It was necessary for the pilot to fly past an airport control tower to confirm that the TR was stationary.</td></tr>
<tr><td>Action:</td><td colspan="5">Run-on landing was attempted.</td></tr>
<tr><td>Effect:</td><td colspan="5">The helicopter was damaged on landing.</td></tr>
<tr><th colspan="6">Possible impact of HUMS prevention and mitigation technologies</th></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated to the pilot that the TR was stationary, the pilot could then deduce that the fin must be undamaged as the aircraft still had directional stability.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The information should have prompted the pilot to reduce torque to maintain level flight, maintain airspeed above 40 knots, if necessary fly to a suitable landing area, and carry out an engine-off or run-on landing.</td></tr>
<tr><td>Effect:</td><td colspan="5">Aircraft damage may have been minimised, but this would be affected more by pilot handling knowledge and training than by any HUMS information.</td></tr>
<tr><th colspan="6">Application of non-HUMS prevention and mitigation technologies</th></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">The basic aircraft exhibited sufficient yaw stiffness to enable continued flight at a reduced power level. A cambered inflatable fin, variable camber fin or drag chute would have reduced the speed necessary to maintain heading during a run-on landing. A ducted fan would have sustained the engine cover impact assuming the duct was strong enough. A twin TR system would have provided redundancy assuming the second system remained intact. A robust TRDS would have absorbed the shock impact and allowed TR drive to be recovered. However the advantages of good fuselage yaw stiffness without the TR functioning are demonstrated by this occurrence. Additional training for this type of emergency would have resulted in the pilot using a different landing technique, i.e. the landing would have been better accomplished using an engine-off technique.</td></tr>
</table>

3.4 **Occurrence No. 5 (an object hit the TR)**

3.4.1 **Key details**: see Table A-10:

Table A-10 Occurrence No. 5 (an object hit the TR) - key details

Aircraft type/registration:	Super Puma G-BKZH
Date and time:	20 May 1987 at 1350 hours
Location:	35 nm east-north-east of Unst, Shetland Isles
Operator/type of flight:	Public transport
Injuries:	None
Nature of damage:	Tail pylon almost severed
Information source:	AAIB Aircraft Accident Report No 9/88

3.4.2 **History of the flight**: The aircraft lifted-off from Sumburgh at 1300 hours and climbed to 3,000 feet. The flight progressed normally until, at 1350 hours, the aircraft suddenly began to vibrate severely and pitched nose-up, to an angle of approximately 30°.

The commander immediately lowered the collective pitch lever, reducing the MR blade pitch angle from 15.5° to 12° and, consequently, the anti-torque loading on the TR. At the same time, he corrected the aircraft's nose-up attitude and established a gentle rate of descent. The vibration suddenly reduced to a tolerable level and it became apparent that continued flight was possible. Both pilots immediately deduced that the problem was emanating from the TR and decided to respond in accordance with the procedure laid down for a "TRCF". The drill for this event precludes the use of the yaw pedals and requires minimal movement of the collective pitch lever.

The crew headed towards the nearest land, the island of Unst some 35 nm distant. The commander made a straight-in approach and safely executed a run-on landing without the use of yaw pedals and at the 12° of collective pitch already set. The occupants disembarked normally.

3.4.3 **Findings of the accident investigation**: An inspection revealed that two TR blades had suffered leading edge damage and one of these had a large section of its trailing edge missing. The tail pylon was almost severed just below the TR gearbox mountings.

The lower segment of the Inclined Driveshaft (IDS) fairing landing channel became detached in-flight and collided with the TR, resulting in the detachment of a substantial portion of the trailing edge of one TR blade. The imbalance caused by this detachment generated excessively high loads in the pylon structure which almost caused total failure of the pylon structure immediately below the TR gearbox (TRGB) attachment. Whilst the vibration was progressively cracking and weakening the tail pylon structure, the commander was unaware of the increasingly critical nature of this damage. The TRGB was near to complete detachment when the aircraft landed.

Had the upper part of the pylon separated, a total loss of control very similar to that experienced by another AS332, G-TIGD at Aberdeen in 1983 (Ref: Accident Report 4/84) could have occurred. In this occurrence 10 of the 16 passengers on board were seriously injured when the helicopter crashed on the runway after a loss of control occurred at 50 feet agl. Control was lost as a result of in-flight detachment of the TR assembly, together with the TRGB and upper pylon structure, due to excessive rotor imbalance forces following damage to the TR blades. This damage had occurred due to contact between the blades and the IDS fairing.

3.4.4 **Analysis**: see Table A-11:

Table A-11 Occurrence No. 5 (an object hit the TR) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">TR hit by segment of fairing</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Tail pylon almost severed</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR problem was correctly diagnosed</td></tr>
<tr><td>Action:</td><td colspan="5">Diversion and run-on landing</td></tr>
<tr><td>Effect:</td><td colspan="5">Helicopter landed successfully, but a potentially catastrophic loss of control was only narrowly avoided</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">An on-demand vibration check or continuous rotor vibration monitoring could have indicated the severity of the damage, and possibly the progressive nature of the pylon cracking (assuming that the sensor was serviceable).</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot may have elected to ditch the aircraft rather than continue the flight.</td></tr>
<tr><td>Effect:</td><td colspan="5">If only by good fortune, the outcome of the occurrence was satisfactory, it must therefore be concluded that a HUMS could not have improved on this outcome.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">An inflatable fin, variable camber fin or drag chute would have increased the aircraft's yaw stiffness enabling the pilots to reduce TR pitch further in order to achieve the minimum vibration levels induced by the out of balance TR, this in turn would have reduced the fatigue cracking at the base of the fin. Implicit in the assumed use of a variable cambered fin is that it was not part of, or affected by the initial separation of the fairing. A ducted fan could have sustained the fairing impact and avoided damage to the TR. A twin TR system would have provided redundancy assuming the second system remained intact. This occurrence does serve to illustrate the importance of secure retention of drive shaft covers and the importance of ensuring that the cover hinges away from the TR. In addition the loss of the leading edge of the fin reduces its capability to generate aerodynamic lift and therefore off-loading of the TR and also reduces the fuselage weathercock stability.</td></tr>
</table>

3.5 **Occurrence No. 6 (an object hit the TR)**

3.5.1 **Key details**: see Table A-12:

Table A-12 Occurrence No. 6 (an object hit the TR) – key details

Aircraft type/registration:	Puma HC1 XW233
Date and time:	6 June 1989
Location:	1 nm west of Crossmaglen
Operator/type of flight:	RAF
Injuries:	None
Nature of damage:	Category 3 damage
Information source:	IFS(RAF)

3.5.2 **History of the flight**: While lifting an underslung load of metal plates a piece of plastic sheeting suddenly flew up in the region of the TR. A bang was felt followed by severe vibration throughout the airframe. The aircraft immediately started to yaw left. Diagnosing a TR the pilot pulled back the throttles. The landing was cushioned with the collective. The aircraft came to rest at about 15° to 20° nose-down and left side low.

3.5.3 **Findings of the accident investigation**: The occurrence was caused by the ingestion of a large plastic sheet into the TR. The TR blades were damaged and the horizontal drive shaft sheared.

3.5.4 **Analysis**: see Table A-13:

Table A-13 Occurrence No. 6 (an object hit the TR) - analysis

<table>
<tr><th colspan="6">Occurrence information</th></tr>
<tr><td>Failure mode:</td><td colspan="5">TR hit by plastic sheeting</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Lifting underslung load</td></tr>
<tr><td>Consequence:</td><td colspan="5">Category 3 damage to aircraft</td></tr>
<tr><th colspan="6">Pilot information and response</th></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR was correctly diagnosed</td></tr>
<tr><td>Action:</td><td colspan="5">Correct action was taken during the subsequent landing</td></tr>
<tr><td>Effect:</td><td colspan="5">Helicopter damage was minimised</td></tr>
<tr><th colspan="6">Possible impact of HUMS prevention and mitigation technologies</th></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot but there was insufficient time for the pilot to make use of this information.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot required no prompting on the action to take.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS could not have affected the outcome of the occurrence.</td></tr>
<tr><th colspan="6">Application of non-HUMS prevention and mitigation technologies</th></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Engine throttles or chop switch located on the collective might have aided the pilot, however the outcome would have still been the same. The limited time between failure and ground contact precluded the use of any of the emergency devices like drag chute. A ducted fan could have escaped the plastic sheet impact and avoided damage to the TR. A twin TR system would have provided redundancy assuming the second system remained intact.</td></tr>
</table>

4 Failure of the tail pylon structure

4.1 Occurrence No. 7 (failure of the tail pylon structure)

4.1.1 **Key details**: see Table A-14:

Table A-14 Occurrence No. 7 (failure of the tail pylon structure) - key details

Aircraft type/registration:	Bell 214ST G-BKFN
Date and time:	24 December 1990 at 1856 hours
Location:	Near the Cormorant A platform in the North Sea
Operator/type of flight:	Public transport
Injuries:	None
Nature of damage:	Serious failure of fin structure
Information source:	AAIB Bulletin No 9/91

4.1.2 **History of the flight**: The crew were to fly from Unst, at the north of Shetland, to the Cormorant A platform from where they were to carry out a series of inter-rig shuttle flights to the Safe Supporter accommodation vessel which was located close to the Dunlin A platform, some 20 nm to the north-east.

The helicopter departed from Unst at 1716 hours, arrived at the Cormorant A platform, and then completed two return trips to the Safe Supporter. Having completed their first inter-rig shuttle task, the crew intended flying to the Dunlin A platform to refuel prior to a further shuttle task. There were no passengers or freight on board and, given the aircraft's light weight and the prevailing wind, the co-pilot needed to use only 70% torque for the take-off. On becoming airborne, the helicopter was accelerated to 80 knots and turned while climbing to 500 feet.

At 500 feet the co-pilot levelled the aircraft and allowed it to accelerate. On reaching 110 knots, the crew became aware of a low amplitude vibration with a frequency somewhere between a 'buzz' and 'once per rotor-revolution'. There was no associated noise, no handling problem and no indication on the flight deck instruments to indicate a malfunction of any of the aircraft's systems. The commander took control of the aircraft and lowered the collective lever slightly to reduce speed, while maintaining height. As the speed reduced, an additional vibration with a frequency of about one or two per rotor-revolution was noted. On passing 100 knots the crew observed a pronounced lateral cyclical movement which persisted until the speed had fallen below 90 knots. By 80 knots, all vibration had reduced to negligible amplitude and this speed was maintained.

The commander decided to abandon his planned flight to the Dunlin A and divert to the Safe Gothia accommodation vessel which was alongside Brent B platform some 20 miles to the east. The diversion was uneventful and the aircraft landed at 1918 hours following a 29 minute flight.

4.1.3 **Findings of the accident investigation**: An initial inspection aboard the Safe Gothia revealed cracks in the fin root structure, in the zone around the 42° gearbox, in both the left hand side skin and the inclined fin front spar web fitting. This cracking was deemed sufficiently serious to preclude further flight before the tailboom/fin had been replaced.

Subsequent investigation showed that the crack in the fin front spar web had progressed across about 80% of the spar width and the crack in the left side skin had progressed about halfway towards the fin rear spar. This had resulted in a major degradation of the strength and stiffness of the fin attachment. The position of the crack in the spar web was in such a location that, in normal service, the presence of the 42× gearbox at the fin root and the natural oiliness and dirtiness of the zone would have made the crack difficult to see during routine inspections.

A metallurgical examination revealed that the mechanism of crack initiation and progression in both the spar web and the skin had been by fatigue which had nucleated, in the spar, from a poorly finished rivet hole, and in the two rivet holes just aft of a doubler patch on the left side skin. The fatigue cracks appeared to have propagated steadily at first but the rate had accelerated during the later stages. Evidence of fatigue and shear failures in two rivets between the fatigue cracks suggested that they failed completely at the same time and, by joining the two cracks, led to the apparently sudden change in the stiffness characteristics. Although fatigue striations were clearly visible it was not possible to identify any particular load cycle and thereby make an assessment of the period of fatigue growth.

4.1.4 **Analysis**: see Table A-15:

Table A-15 Occurrence No. 7 (failure of the tail pylon structure) - analysis

Occurrence information	
Failure mode:	Serious cracking of the fin structure.
Phase of flight:	After accelerating to cruising speed.
Consequence:	Diversion.
Pilot information and response	
Warning:	The crew sensed an unusual vibration and aircraft motion.
Diagnosis:	The crew would have been aware that the TR was functioning but probably had little information on the nature of the failure.
Action:	The crew reduced speed and diverted.
Effect:	A successful landing was achieved.
Possible impact of HUMS prevention and mitigation technologies	
Warning:	It is not possible to determine whether TR, shaft or gearbox vibration monitoring could have provided a warning of the developing cracks in the fin structure.
Diagnosis:	An on demand vibration check or continuous rotor vibration monitoring could have identified the TR as the source of the unusual vibration, and given information on whether the situation was deteriorating.
Action prompt:	The action to take should be determined by the pilot
Effect:	A HUMS might have detected the failure and prevented the flight taking place, but it would probably not have changed the actions of the crew during the flight.
Comment	None.

4.2 Occurrence No. 8 (failure of the tail pylon structure)

4.2.1 **Key details**: see Table A-16:

Table A-16 Occurrence No. 8 (failure of the tail pylon structure) - key details

Aircraft type/registration:	Super Puma G-BWMG
Date and time:	28 January 1998 at 16226 hours
Location:	40 nm east of Sumburgh
Operator/type of flight:	Public transport
Injuries:	None
Nature of damage:	Horizontal stabiliser detached
Information source:	AAIB Bulletin No 8/98

4.2.2 **History of the flight**: The aircraft took off from the Tern Platform at 1553 hours, heading for Aberdeen. At 1626 hours, while cruising at 130 knots and 2,500 feet AMSL, the crew heard a loud bang. The helicopter pitched rapidly nose-down and yawed to the right. The autopilot then disengaged and the commander partially lowered the collective lever. There was a short period of pitch oscillation before the helicopter settled into a steady descent. The commander regained adequate control of the helicopter at about 1,600 feet AMSL and increased power to climb initially to 2,000 feet. The co-pilot informed Air Traffic Control (ATC) that they were having trouble with the yaw pedals and that they suspected that there was something wrong with the tail. The aircraft diverted to Sumburgh, by 1629 hours the helicopter was again cruising at 2,500 feet but at a reduced power setting. The commander reached the conclusion that the problem might be associated with the horizontal stabiliser.

An S61 approached the helicopter to act as an escort, at 1641 hours the S61 crew confirmed that the horizontal stabiliser had detached cleanly and completely. After discussing the problem with another company AS332 commander, some passengers were re-seated to compensate for the change in centre of gravity. The crew decided to perform a run-on landing, and landed without incident at 1649 hours.

4.2.3 **Findings of the accident investigation**: A metallurgical investigation revealed that the stabiliser spar had failed due to a fatigue crack that had initiated as a result of a combination of corrosion micropitting and reduced material strength. A sudden change to rapid crack growth that preceded the failure of the spar was not explained. One suggestion was that the normal vibratory loads in the spar might have been amplified due to the accumulation of ice on the stabiliser.

Following the incident the Integrated HUMS (IHUMS) data was examined. The TR gearbox input shaft vibration trace showed a three-fold increase in magnitude during the last three hours prior to the separation of the stabiliser. This was thought to be a function of the decreasing stiffness of the stabiliser, as the crack in the spar progressed, which excited the accelerometer mounted on the TR gearbox.

4.2.4 **Analysis**: see Table A-17:

Table A-17 Occurrence No. 8 (failure of the tail pylon structure) - analysis

Occurrence information	
Failure mode:	Detachment of the horizontal stabiliser
Phase of flight:	Cruise flight
Consequence:	Diversion
Pilot information and response	
Warning:	None reported
Diagnosis:	With the aid of an escorting aircraft, the crew diagnosed the loss of the horizontal stabiliser.
Action:	The crew diverted and performed a run-on landing.
Effect:	The helicopter landed safely.
Possible impact of HUMS prevention and mitigation technologies	
Warning:	Vibration monitoring may have provided warning of the increased TR gearbox input shaft vibration prior to the stabiliser failure if this information could be displayed in the cockpit.
Diagnosis:	The HUMS could not have diagnosed the horizontal stabiliser failure.
Action prompt:	Any additional HUMS information would have been unlikely to affect the actions of the pilot.
Effect:	As the aircraft was HUMS equipped, it must be concluded that the HUMS could not have prevented the flight taking place on which the failure occurred, and could not affect the outcome of this incident.
Comment	None.

5 Failure of the TR gearbox mounting

5.1 Occurrence No. 9 (failure of the TR gearbox mounting)

5.1.1 **Key details**: see Table A-18:

Table A-18 Occurrence No. 9 (failure of the TR gearbox mounting) - key details

Aircraft type/registration:	Bell UH-1B N3979C
Date and time:	23 September 1993
Location:	Pierce, ID, USA
Operator/type of flight:	Unknown
Injuries:	None
Nature of damage:	Collapse of skids and loss of tail boom
Information source:	NTSB summary SEA93LA207

5.1.2 **History of the flight**: Whilst manoeuvring near a refuelling site in hilly/mountainous terrain, the TR gearbox separated from the aircraft. The pilot attempted a run-on forced landing on a nearby logging road. During the flare the aircraft landed hard, resulting in a collapse of the skids and separation of the remaining portion of the tail boom.

5.1.3 **Findings of the accident investigation**: An investigation revealed that all six gearbox attachment bolts had experienced reverse-bending fatigue failure.

5.1.4 **Comment on the findings of the accident investigation**: It is it is considered unlikely that all six bolts suffered reverse bending fatigue failure. It is more likely that either one bolt suffered fatigue and the extra effects on the remaining bolts were such that they progressively suffered fatigue, or that the cracking was initiated by a transient overload which initiated cracks (thereby removing the initiation phase) and the bolts subsequently failed in a traditional fatigue. It is therefore possible that poor maintenance/inspection practices were a contributory factor in the occurrence of the occurrence.

5.1.5 **Analysis**: see Table A-19:

Table A-19 Occurrence No. 9 (failure of the TR gearbox mounting) - analysis

Occurrence information					
Failure mode:	Detachment of the TR gearbox				
Phase of flight:	Manoeuvring at low altitude				
Consequence:	Damage to aircraft				
Pilot information and response					
Warning:	None reported				
Diagnosis:	The crew apparently diagnosed a loss of TR authority				
Action:	The crew attempted a run-on landing				
Effect:	The helicopter landed hard				
Possible impact of HUMS prevention and mitigation technologies					
Warning:	Gearbox vibration monitoring would have detected any high vibratory loadings which caused the failure of the gearbox attachment bolts.				
Diagnosis:	The TR sensors would have been destroyed when the gearbox detached, therefore no diagnosis would be possible.				
Action prompt:	The pilot required no prompting on the action to take.				
Effect:	A HUMS should have prevented this occurrence, however it could not have affected the outcome of the occurrence once the failure had occurred.				
Application of non-HUMS prevention and mitigation technologies					
Technologies applicable	**DC**	**IF**	SBU	FBW	SLP
	HYD	SRU	BUCS	AFCS	ECS
	DF	**TTDD**	VCF	CNR	RSDS
Comment	In the short duration between failure and ground contact, the use of a drag chute would have aided the pilot in reducing his run-on landing speed, however, the final outcome would still have been the same. The inflatable fin might have generated a little addition yaw damping as the aircraft began to spin, however the final outcome would have been the same. There would have been the additional risk that the loads imparted by the drag chute or the inflatable fin, on the tail boom, would have caused an earlier separation of the tail boom. An in-line ducted fan would not have had a TRGB. A twin TR system would have provided redundancy assuming the second system remained intact.				

6 Failure of the TR drive shaft

6.1 Occurrence No. 10 (failure of the TR drive shaft)

6.1.1 **Key details:** see Table A-20:

Table A-20 Occurrence No. 10 (failure of the TR drive shaft) - key details

Aircraft type/registration:	Bell 206B Jetranger III C-FPQS
Date and time:	1994
Location:	Canada
Operator/type of flight:	Underslung load work
Injuries:	Minor
Nature of damage:	Substantial damage to helicopter
Information source:	Transportation Board of Canada Report

6.1.2 **History of the flight:** The helicopter was carrying a sling load. The pilot transitioned into a hover and began a vertical descent to set the load on the ground. When the load was approximately 2 feet off the ground (helicopter height approximately 25 feet), the helicopter departed from controlled flight and rotated violently to the right through three rotations. The helicopter struck the ground and rolled onto the right side. The pilot sustained minor injuries.

The pilot was aware that there was a person on the ground under the helicopter when a loss of TR thrust occurred. He immediately lifted the collective and attempted to manoeuvre away from the person and a building. The helicopter travelled approximately 50 feet before impact. The pilot did not release the sling load to avoid the risk of dropping the load on the person on the ground. The pilot did not attempt to enter autorotation due to the altitude, the low airspeed, and the perilous location of the person on the ground.

6.1.3 **Findings of the accident investigation:** The Bell 206B Jetranger III TR drive system consists of a forward short shaft, an oil cooler fan drive shaft, an aft short shaft, and five TR dive shaft segments. Steel-laminated flexible couplings are used to connect the shaft sections. Visual examination of the wreckage showed that the aluminium aft short TR drive shaft had failed in the vicinity of the forward bonded coupling.

An examination of the failed shaft identified an area of intergranular cracking initiating from corrosive attack of the interior wall of the shaft, and an area of final overload fracture. The intergranular cracking occupied greater than 35% of the cross sectional area of the shaft. The corrosion cracking must have started before the helicopter was imported to Canada (over a year before the occurrence), when it operated for approximately 11 years in the Arabian Gulf.

It was concluded that:

- The aft short TR drive shaft failed in an area weakened by intergranular cracking which had progressed from corrosion on the interior wall of the drive shaft. The corrosion which existed in the bore of the shaft was not visible with the drive shaft installed.
- The failure of the drive shaft resulted in a loss of TR thrust which occurred when the helicopter was hovering at an altitude which precluded a successful autorotation.

- The pilot successfully manoeuvred the gyrating helicopter away from the person on the ground and a building before impact.

6.1.4 **Analysis:** see Table A-21:

Table A-21 Occurrence No. 10 (failure of the TR drive shaft) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of the TR drive shaft</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Hover/descent with underslung load</td></tr>
<tr><td>Consequence:</td><td colspan="5">Substantial damage to the helicopter</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot was apparently immediately aware of a loss of TR thrust.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot manoeuvred the helicopter away from a person and building and landed.</td></tr>
<tr><td>Effect:</td><td colspan="5">Successful prevention of any serious injury.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">Vibration monitoring may have detected the crack in the TR drive shaft prior to the final failure of this shaft.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot but there was insufficient time for the pilot to make use of this information.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot required no prompting on the action to take.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS may have prevented the occurrence by detecting the crack in the tail drive shaft, but could not have affected the outcome of the occurrence once the failure had occurred.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">The use of a drag chute or inflatable fin would have helped to reduce the yaw rate and provided some yaw stiffness once translational flight was entered and thus helped the pilot to achieve a safer landing. A twin TR system would have provided redundancy and prevented the accident.</td></tr>
</table>

6.2 **Occurrence No. 11 (failure of the TR drive shaft)**

6.2.1 **Key details:** see Table A-22:

Table A-22 Occurrence No. 11 (failure of the TR drive shaft) – key details

Aircraft type/registration:	SA341G Gazelle 1 G-RIFF
Date and time:	7 March 1993 at 0905 hours
Location:	Daresbury, near Runcorn, Cheshire
Operator/type of flight:	Private
Injuries:	None
Nature of damage:	Severe damage to the airframe and rotors
Information source:	AAIB Bulletin No 5/90

6.2.2 **History of the flight:** During a flight from Burton-on-Trent to Warrington, at an altitude of 2,000 feet, the pilot experienced a sudden change in the position of the yaw pedals and realised that he had some form of TR malfunction. However, as he could maintain the helicopter in straight and level flight, albeit with the right skid low, the decision was made to continue rather than attempt an immediate landing.

On reaching the destination ground speed was reduced in the normal manner for an in-to-wind approach to hover but, as power was increased, the pilot realised that he had no TR control. The helicopter began to yaw to the left, and then completed four or five turns before striking the ground and rolling over. There was no fire and the pilot, who was uninjured, was able to make his escape.

6.2.3 **Findings of the accident investigation**: Examination of the aircraft showed that the TR drive shaft had failed at a position where it passed through a cut-out in the rear of the MR gearbox fairings. The reason for this failure was that the rear of the right side fairing had been bearing against it as a result of a failure of the fairing itself. The forward two thirds of this fairing was missing, having detached from the helicopter in flight. This had allowed the 'leading edge' of the rear portion to rotate outboard and force its 'trailing edge' against the shaft.

In an investigation in conjunction with the Army Air Corps (who operate a fleet of military SA341 Gazelle helicopters) it was established that high vibration levels exist in this area of the helicopter and that there have been a number of instances where fairing latches have failed, or have come undone, leading to TR drive shaft damage. Without all of the latching components from the fairing front and side latches it was not possible to determine if these had suffered any failure in flight. It was not possible to determine whether the front latch had unlocked due to vibration in flight, or had not been locked beforehand.

6.2.4 **Comment on the findings of the accident investigation**: This occurrence has been classified as a TR drive shaft failure, the cause of which was rubbing of a fairing against the shaft. It is recognised that the actual cause of this rubbing, and therefore the root cause of the occurrence, was a failure of the fairing latches. However the inclusion of the occurrence here is justified on the basis that it provides a good example of a particular shaft failure mode - contact between a rotating shaft and a fixed part of the aircraft structure.

6.2.5 **Analysis**: see Table A-23:

Table A-23 Occurrence No. 11 (failure of the TR drive shaft) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of the TR drive shaft</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Substantial damage to aircraft</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot did not appear to be aware that he had no TR thrust until at a late stage of the occurrence.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot failed to take the correct action and perform an autorotative landing.</td></tr>
<tr><td>Effect:</td><td colspan="5">The landing was not properly controlled; the aircraft struck the ground and rolled over.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">Vibration monitoring of the TR drive should have detected the fairing rubbing against the shaft, it is not possible to determine how much warning prior to the shaft failure this would have provided</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The information should have prompted the pilot to perform an engine-off or run-on landing.</td></tr>
<tr><td>Effect:</td><td colspan="5">Aircraft damage could have been minimised.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">This occurrence illustrates the benefits of a large cambered fin in forward flight which off-loads the TR. As a consequence, the failure of the drive shaft resulted in only a small loss of TR thrust and therefore only a small change in aircraft trim state. An inappropriate landing technique was used, resulting in the aircraft crashing.
The existing fin off-loading would have been improved by the use of a variable camber fin or an inflatable fin during forward flight. The recovery method employed would also have benefited from the use of a drag chute, which would have helped maintain heading when the fin devices became less effective at low speed. A twin TR system would have provided redundancy although both TRDSs could have been damaged.</td></tr>
</table>

6.3 Occurrence No. 12 (failure of the TR drive shaft)

6.3.1 **Key details**: see Table A-24:

Table A-24 Occurrence No. 12 (failure of the TR drive shaft) - key details

Aircraft type/registration:	Sea King HAS Mk6 XV654
Date and time:	21 July 1993
Location:	Prestwick Airfield
Operator/type of flight:	RN
Injuries:	None
Nature of damage:	Category 4 damage
Information source:	RN Accident Report No 3/93

6.3.2 **History of the flight**: As the aircraft was brought into the hover before landing it yawed right. Full left pedal was applied to no effect, a 'clunk' noise was heard from the rear of the aircraft and N_R was heard to rise.

The pilot immediately lowered the collective lever and as the aircraft impacted the ground still yawing he retarded the speed select levers. The port sponson detached and the MR blades impacted the ground on the port side of the aircraft. The aircraft came to rest on the hull, listed to port, and the crew vacated the aircraft.

6.3.3 **Findings of the accident investigation**: The number 4 TR drive shaft had sheared immediately aft of the viscous damper bearing. The shaft had been cracked for some time but this was not detected as the shaft collar hid the defect. There was evidence of the tail drive shaft having run out of alignment.

6.3.4 **Analysis**: see Table A-25:

Table A-25 Occurrence No. 12 (failure of the TR drive shaft) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of the TR drive shaft</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Hover prior to landing</td></tr>
<tr><td>Consequence:</td><td colspan="5">Category 4 damage to aircraft</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot apparently correctly diagnosed a loss of TR drive.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot responded immediately by lowering the collective.</td></tr>
<tr><td>Effect:</td><td colspan="5">The consequences of the occurrence were minimised as far as possible.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">TR drive shaft vibration monitoring should have detected that the shaft was running out of alignment.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot but there was insufficient time for the pilot to make use of this information.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot required no prompting on the action to take.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS should have prevented the occurrence by detecting a misaligned tail drive shaft, but could not have affected the outcome of the occurrence once the failure had occurred.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">As the aircraft was close to the ground, there was insufficient time for the pilot to react in any other way than he did. A twin TR system would have provided redundancy and prevented the accident. No other technologies would have helped in this case.</td></tr>
</table>

6.4 **Occurrence No. 13 (failure of the TR drive shaft)**

6.4.1 **Key details**: see Table A-26:

Table A-26 Occurrence No. 13 (failure of the TR drive shaft) - key details

Aircraft type/registration:	Wessex HC2 XR524
Date and time:	12 August 1993
Location:	Llyn Padarn, North Wales
Operator/type of flight:	RAF
Injuries:	3 fatalities, 1 serious injury
Nature of damage:	Category 5 damage
Information source:	D/IFS(RAF)/140/86/93/1

6.4.2 **History of the flight**: The sortie was primarily a SAR mission management exercise, and was planned to include a simulated emergency. Whilst flying along the edge of Llyn Padarn at approximately 500 feet agl, the pilot initiated a simulated yaw channel runaway condition by gently applying a small amount of left pedal together with compensatory right bank.

As the aircraft entered a gently descending right turn, the pilot raised the collective lever. Shortly afterwards, when the aircraft had turned through approximately 180°, with an airspeed of 50-60 knots, a loud bang was heard to the rear of the cabin. The aircraft immediately yawed to the right and pitched slightly nose-up.

In an attempt to establish a power/airspeed combination to maintain stable flight, the pilot responded by lowering the collective lever and selecting an accelerating, slightly nose-down aircraft attitude. Although the nose-down attitude was not maintained, it appeared initially that stable flight had been achieved until approximately 16 seconds after the failure when, at a height of about 400 feet, an uncontrollable yaw to the right began.

As the airspeed fell to zero, the pilot confirmed that the collective lever was fully down and fully retarded both speed select levers before arming the flotation gear. After calling "ditching", he raised the collective lever at about 150 feet in an effort to cushion the aircraft impact. The aircraft struck the surface of the lake with considerable vertical force approximately 34 seconds after the initial failure. The aircraft quickly inverted and sank nose first. The salinity of the water was too low to activate the flotation system.

6.4.3 **Findings of the accident investigation**: The cause of the crash was a failure in the TR drive train. The No 3 TR drive shaft had failed in the region of its forward attaching flange which connects it to the No 2 shaft.

The shaft had been stressed beyond its design limits whilst being driven in its normal direction of rotation. The following hypothesis of the sequence of events was considered to be the most probable cause of the occurrence:

- The tail fold disconnect coupling had become stiff to operate during service. The tail pylon was folded at some unknown time. When the tail pylon was subsequently unfolded, the coupling flange teeth were in crown-to-crown contact.
- At some stage the coupling flanges rotated relative to one another, but this only resulted in a marginal engagement of the flange teeth by 1 mm. The coupling was capable of transmitting the loads experienced during normal flight. However, the

simulated yaw channel runaway manoeuvre involved the application of considerable sideforce, which with the resultant requirement for higher TR thrust, generated a high load on the tail structure. This caused increased bending forces in the tail boom, which tended to stretch the transmission train, and resulted in the minimal engagement of the disconnect coupling being lost.

- The loss of drive to the TR allowed its speed to decay. This relieved the previously imposed bending stresses on the tail boom, and allowed the coupling to re-engage. The resultant shock loading of the transmission train was sufficient to cause failure of the No 3 shaft.

The following findings related to aircraft handling during the occurrence:

- Shortly after the aircraft appeared to achieve stabilised flight, the nose began to rise and the aircraft decelerated. The aircraft was now close to its critical yaw angle, beyond which airflow separation over the rear fuselage/tail pylon occurs, thereby removing its yaw stabilising, ‘weather-cock’ effect. This angle appears to have been reached after 13 seconds of stable flight, when the yaw began to increase significantly.
- As the aircraft rapidly diverged to the right, the airspeed quickly fell to zero. With the aircraft spiralling towards the lake at over 3,600 ft/min at zero airspeed and a lower than normal rotor speed, it was considered that autorotation had not been achieved and it had become impossible to arrest the rate of descent.

It was noted that the advice on TRs contained in the Aircrew Manual and Flight Reference Cards, while not inaccurate, was incomplete, and that there was a lack of adequate training for such an emergency.

6.4.4 **Analysis**: see Table A-27:

Table A-27 Occurrence No. 13 (failure of the TR drive shaft) - key details

<table>
<tr><th colspan="6">Occurrence information</th></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of the TR drive shaft</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Simulated yaw channel runaway condition</td></tr>
<tr><td>Consequence:</td><td colspan="5">Fatal occurrence</td></tr>
<tr><th colspan="6">Pilot information and response</th></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot's diagnosis of the failure is unclear.</td></tr>
<tr><td>Action:</td><td colspan="5">Airspeed was allowed to decay and yaw angle increase so that controlled forward flight could not be maintained, it was then too late to enter autorotation.</td></tr>
<tr><td>Effect:</td><td colspan="5">A spiralling descent resulted in the aircraft impacting the lake with considerable vertical force.</td></tr>
<tr><th colspan="6">Possible impact of HUMS prevention and mitigation technologies</th></tr>
<tr><td>Warning:</td><td colspan="5">The disconnect coupling was apparently not correctly engaged for some time before the occurrence. Vibration monitoring should have detected a resulting abnormal shaft vibration prior to the high load manoeuvre which caused the shaft failure.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated the initial loss of TR drive to the pilot, however it is unlikely that the pilot would have been able to make use of this information.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">It is not possible to say whether the diagnostic information could have enabled the pilot to make a more controlled ditching.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS should have prevented the occurrence, but it would have been unlikely to affect the outcome of the occurrence once the failure had occurred.</td></tr>
<tr><th colspan="6">Application of non-HUMS prevention and mitigation technologies</th></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">A drag chute or inflatable fin should have enabled the pilot to regain control following the TRDF and achieve a power speed combination albeit with a gentle descent. The final landing would have depended upon the circumstances at the time but would most probably be best to undertake an engine-off rather than attempting a run-on landing. The use of a variable camber fin which off-loaded the TR in forward flight would have enabled the flight to continue although most likely not in a fully trimmed condition. A twin TR system would have provided redundancy and prevented the accident.</td></tr>
</table>

7 Failure of a TR drive shaft spline coupling

7.1 Occurrence No. 14 (failure of a TR drive shaft spline coupling)

7.1.1 **Key details**: see Table A-28:

Table A-28 Occurrence No. 14 (failure of a TR drive shaft spline coupling) - key details

Aircraft type/registration:	Bell 212 OY-HMC
Date and time:	2 January 1984 at 1813 hours
Location:	20 nm east of the Dan-B platform, North Sea
Operator/type of flight:	Public transport
Injuries:	3 fatalities
Nature of damage:	Substantial damage to the aircraft
Information source:	Danish Department of Accident investigation

7.1.2 **History of the flight**: The aircraft departed from Esbjerg airport at 1702 hours on a flight to the Gorm Charlie oil rig in the North Sea. The outbound altitude initially was 500 feet. At 1810 hours the aircraft contacted Gorm Charlie for the routing to be executed in the Gorm area.

At about 1813, during cruise at approximately 1,000 feet, the crew transmitted a MAYDAY call, which was picked up by the crew of another company helicopter operating in the Gorm area. The transmission lasted approximately 15 seconds. No subsequent contact could be made with the aircraft.

The aircraft was ditched in the North Sea on a dark evening during Visual Meteorological Conditions, under conditions of Sea State 6 and high winds approximately 80 nm west of Esbjerg and approximately 35 nm east southeast of destination Gorm Charlie.

7.1.3 **Findings of the accident investigation - CVR analysis**: The voice communication and sound track clearly revealed that the crew were suddenly faced with a technical problem which under the operational conditions (darkness, turbulent air, and the nature of the technical failure), made an identification of the failure extremely difficult. Time from the onset of failure to the ditching was 1 minute and 17 seconds.

The 70 Hz TR drive shaft frequency begins to drop out within 1 second of a noise (whine) which is clearly audible on the tape (time = 0 seconds), indicating a disengagement of the TR drive. The elapsed time from the onset of whine to impact is 76.2 seconds. The start of the failure sequence takes place at minus 32.6 seconds prior to the whine when the TR signal increases indicating that a load increase within the gear train is developing. At intervals the signal picks up slightly, indicating that the disengagement is not at this time complete, as there is an indication that the TR drive shaft engages intermittently in the process of the failure.

7.1.4 **Findings of the accident investigation - The TR output quill coupling failure**: Examination of the coupling mounted on the TR drive quill assembly, which functions as the first flexible joint of the TR drive train, revealed a spline failure of the external spline section. The external splines on this coupling were totally ground off and showed evidence of excessive overheat and smearing of the metal. Further evidence showed that at the time of impact the TR drive shaft had only little rotational speed as no power could be applied due to the disconnect.

The flexible couplings on OY-HMC had been inspected, serviced and lubricated about 15 flying hours prior to the occurrence. The daily service involved a visual inspection of all the TR drive couplings. The TR drive quill coupling is inspected for grease leakage and visual overheat stripes (indicator stripes attached to the outer coupling) are checked for discoloration indicating an overheat condition. OY-HMC had been subject to such an inspection earlier on the day of the occurrence. As part of the spline coupling was never recovered it could only be concluded that the internal failure of the spline coupling was due to either a material failure or a seal failure, which in both cases would result in loss of lubricant and subsequent increase in temperature. The reason for the spline coupling failure was not conclusively established.

7.1.5 **Analysis of the probable sequence of events**: It is believed that the flight was initially performed at 500 feet AMSL. Until the time of the technical failure the flight appears to have been normal. The wind was quite strong (30 knots) and some turbulence must have been present. It was dark outside. Shortly before establishing contact with Gorm-C the helicopter climbs to about 600-700 feet.

Even though the initial stages leading to the technical failure begin about 32 seconds prior to the failure, the effect of the failure is probably not apprehended by the co-pilot until 7 seconds after the “whine” (at 0 seconds) when he exclaims “What is that?” The whine has presumably not been heard by any of the pilots, but the captain must very shortly after the onset of TR drive disconnection have felt it through the controls and pedals.

After about 10 seconds TR thrust is no longer effectively produced, and yaw control is subsequently lost, although short intervals of re-engagement of the coupling could have produced some sort of intermittent TR thrust during the process of spline failure and melting of the metal parts in the coupling.

The captain almost certainly notices something abnormal instantly when the failure occurs and lowers the collective stick. This reaction dampens the yaw rate which at this time is not violent, as TR thrust is not lost instantaneously. The captain does not express himself and, if the captain had reacted at once, the above factor combined with some degree of turbulence could result in a very hesitant recognition on the part of the co-pilot that something is wrong. This could explain why it takes 24 seconds from the time a highly serious malfunction occurs until a MAYDAY is called.

N_R increases as the load from the TR drops and the collective is lowered immediately after. The co-pilot recognises something is not normal, but gets no response to his questions. The co-pilot’s exclamations at 12 and 17 seconds indicate that he is attempting to get a comprehensive view/understanding of the problem area from the instrumentation. He is most likely unsuccessful, as there are no indications on the instrumentation that would immediately reveal the source of the problem.

At about 20 seconds there is a clear change in sound and audible bladeslapping, possibly because the captain again pulls collective with the result that the helicopter enters a severe right yaw. The co-pilot now transmits the first MAYDAY call. At 29 seconds the source of the problem is still not identified as the co-pilot now starts to “trouble shoot” (29-34 seconds). No answers are received to questions from the co-pilot. A warning as to “speed” is expressed at this stage; speed is probably high. At 37 seconds the co-pilot calls for landing lights, and shortly after he warns on speed and attitude.

Recurring bladeslapping and dropping N_R indicate that the captain pulls collective again. From 44 to 50 seconds the co-pilot continuously calls for “nose-up”. The rate of descent must have been averaging 600-700 feet per minute. This means that most of the descent has been under partly powered flight with the related difficulties in controlling the helicopter.

The co-pilot's voice is not heard for about 7 seconds, but it is clear that he is under high stress and his expressions following (56-60 seconds) indicate bewilderment of what to do to correct the situation. The lack of response to his urgent calls on "too much power" makes the co-pilot realise that ditching is inevitable. A MAYDAY call with a ditching statement is therefore transmitted. The ditching, which must have been fairly hard, takes place at 76 seconds.

The fact that the average rate of descent was under 1,000 feet per minute, and the N_R was varying, indicates that the major part of the emergency phase has been under powered/partly powered flight. (Rate of descent during power-off autorotation is normally approximately 2,000 feet per minute). There is only one possible recovery procedure for loss of TR thrust - cut power and enter autorotation. The accident investigators believed that the pilots had great difficulty in realising the exact type of failure and deciding how to cope with it on a dark night, with lights on in the cockpit and with no conclusive evidence to derive from the instrumentation. Only "seat of the pants" and a lack of response from pedal movement provide evidence as to the nature of the failure. The fact that the disruption of the TR thrust is not instant, but is believed to be intermittent at the beginning, only adds to the pilot's difficulty in identifying the problem and in taking the necessary corrective action. This may possibly also explain the captain's silence as he has great difficulties in his attempts to control the helicopter. The captain's voice is not heard throughout the occurrence.

It was believed that the pilots could not under the prevailing conditions fully control the ditching. The helicopter contacted the sea heavily. Both aft floats had ruptured on water contact. The helicopter is believed to have capsized to the right very quickly after water contact and sank some time later.

7.1.6 **Conclusions:**

- Whilst OY-HMC was flying normally and at low height the TR output quill coupling failed.
- Initially the crew had great difficulty in determining the type of failure and in controlling the helicopter.
- The failure of the external splines on the TR quill coupling and the subsequent loss of anti-torque control made a ditching inevitable.
- The reason for the failure of the splines in the output quill coupling has not been conclusively established.
- OY-HMC capsized very shortly after the ditching in heavy seas, mainly because the floatation gear was partly destroyed by impact damage.
- For undetermined reasons the captain did not express himself during the entire emergency phase.

7.1.7 **Analysis**: see Table A-29:

Table A-29 Occurrence No. 14 (failure of a TR drive shaft spline coupling) - analysis

Occurrence information					
Failure mode:	TR drive shaft spline coupling failure				
Phase of flight:	Cruise flight				
Consequence:	Fatal occurrence				
Pilot information and response					
Warning:	None				
Diagnosis:	It appears that the crew failed to make a timely diagnosis of the failure.				
Action:	The pilot apparently attempts to maintain power flight and struggles to control the aircraft.				
Effect:	The ditching was not fully controlled and the aircraft contacted the sea heavily.				
Possible impact of HUMS prevention and mitigation technologies					
Warning:	None possible				
Diagnosis:	TR rotational speed monitoring could have given the pilots a positive diagnosis of the loss of TR drive.				
Action prompt:	The information should have prompted the pilots to make a controlled descent and ditching.				
Effect:	A HUMS diagnosis of the TRDF should have enabled the pilots to respond much more effectively to the failure, which would probably have resulted in a properly controlled ditching and the saving of lives.				
Application of non-HUMS prevention and mitigation technologies					
Technologies applicable	**DC**	**IF**	SBU	FBW	SLP
	HYD	SRU	BUCS	AFCS	ECS
	DF	**TTDD**	**VCF**	CNR	RSDS
Comment	The use of a drag chute or inflatable fin would have helped the pilot to stabilise the aircraft following the failure and if necessary undertake a more controlled ditching. However, the cockpit voice recorder indicated that the pilot had great difficulty in identifying the failure, and therefore there is the possibility that he would have failed to use the emergency device. The use of a variable cambered fin in forward flight to off-load the TR would have enabled the flight to continue, however, the final landing would have required a fast run-on landing or a power-off landing. Under the circumstances of this occurrence dependant upon fuel load the aircraft might still have been forced to ditch. A twin TR system would have provided redundancy and prevented the accident.				

8 Failure of a TR drive shaft Thomas coupling

8.1 Occurrence No. 15 (failure of a TR drive shaft Thomas coupling)

8.1.1 **Key details**: see Table A-30:

Table A-30 Occurrence No. 15 (failure of a TR drive shaft Thomas coupling) - key details

Aircraft type/registration:	Bell 206B Jetranger III G-OSUE
Date and time:	14 August 1992 at 1137 hours
Location:	Near Crowthorne, Berkshire
Operator/type of flight:	Public transport
Injuries:	2 fatalities, 3 serious injuries
Nature of damage:	Aircraft destroyed
Information source:	AAIB Bulletin No 2/93

8.1.2 **History of the flight**: The aircraft was positioned at a private house. An engineer was present, having been flown in to rectify an electrical problem. Following engine start, the pilot commented on a high frequency vibration which was apparent through the pedals. The engineer held the pedals with his hands and felt a slight high frequency vibration. He offered to check the TR, but the pilot replied that they would check it when they had returned to base. Once the aircraft had lifted into the hover, the vibration could no longer be detected and the helicopter departed at about 1040 hours to return to Blackbushe Airport.

At 1130 hours the helicopter was progressing towards Blackbushe Airport at a ground speed of about 100 knots. Shortly after 1133 hours a short duration noise was made by the helicopter which was variously described, by witnesses on the ground, as a 'sharp crack', 'similar to a car gearbox breaking up' and 'stuttering like a car misfire'. At about 1134 hours, the helicopter began a gentle right turn to the north; the ground speed appeared to reduce to between 80 and 85 knots in this turn.

At about 1135 hours the commander issued a MAYDAY and stated that he had a 'TR'. In a subsequent transmission he said that he was able to maintain height but had a yaw control problem, and that he was going to try to land at Broadmoor Hospital. A witness saw the helicopter manoeuvre at low level before moving to the east of the hospital where it crashed on wooded heathland. The last radar contact was close to the occurrence site, shortly after 1136 hours.

8.1.3 **Findings of the accident investigation**: The TR blades were completely undamaged, and had not been rotating at the time of impact. The aft short shaft drive flange was completely disconnected from the Thomas coupling and both interconnecting bolts and nuts were missing.

There was evidence that one of the bolts joining the aft short shaft to the coupling had come out shortly before the impact, causing the aft short shaft to rotate about the other remaining bolt, rather than both shafts rotating in unison. As a consequence, the drive to the TR had been lost and the forward shaft section had whirled in a conical motion inside the cowling. This process was almost certainly the source of the noise heard by witnesses on the ground. The relative motion of the shafts during the whirling phase would have generated binding and frictional loads which would have tended very rapidly to unscrew the nut on the remaining bolt.

Examination indicated that the first bolt to come out had progressively migrated out of the coupling over a period of time. It was not possible to determine why the nut initially separated from the bolt on the Thomas coupling. It was possible that the nut had cracked or failed, or partially failed, producing a sudden release of clamping pressure rather than the nut having progressively backed-off. It was not possible to determine how long it took for the bolt to migrate out completely but it is likely to have been a period of many hours of operation, probably tens of hours, rather than of minutes.

Whilst the bolt remained engaged, albeit partially, the coupling would have transmitted power satisfactorily and it is unlikely that there would have been any discernible symptoms except perhaps at a very late stage, when the bolt was only just engaged in the coupling. Under these conditions, ‘cocking’ of the bolt could have allowed a slight misalignment of the shafts, possibly to the extent that a slight high frequency vibration, similar to that felt through the pedals immediately after engine start up, might be produced.

This occurrence, which involved a very experienced helicopter pilot, raised questions concerning the possible problems associated with a total loss of drive to the TR, as distinct from a TR pitch control disconnect, or control jam. These problems include the directional stability from the fixed vertical tail surfaces after the loss of the ‘flat plate fin effect’ of a rotating TR.

8.1.4 **Analysis**: see Table A-31:

Table A-31 Occurrence No. 15 (failure of a TR drive shaft Thomas coupling) - analysis

<table>
<tr><th colspan="6">Occurrence information</th></tr>
<tr><td>Failure mode:</td><td colspan="5">TR drive shaft Thomas coupling failure</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Fatal occurrence</td></tr>
<tr><th colspan="6">Pilot information and response</th></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot apparently correctly diagnosed a TR.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot’s actions are unclear, the aircraft should have been controllable without the TR and it may have been a lack of practice that prevented the pilot from making a safe descent and landing.</td></tr>
<tr><td>Effect:</td><td colspan="5">Aircraft crashed</td></tr>
<tr><th colspan="6">Possible impact of HUMS prevention and mitigation technologies</th></tr>
<tr><td>Warning:</td><td colspan="5">Tail drive shaft vibration monitoring may have provided a warning of the bolt migrating out of the coupling prior to the flight, and should have provided a warning during the flight.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The information should have prompted the pilot to fly to a safe area and make a controlled descent and landing.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS warning may have prevented the occurrence, and should have prevented the occurrence if this warning could be given to the pilot. A loss of TR drive indication following the failure would probably not have affected the outcome of the occurrence, as this was probably due more to lack of practice of dealing with tail rotor failures than to a lack of information on the nature of the failure.</td></tr>
<tr><th colspan="6">Application of non-HUMS prevention and mitigation technologies</th></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Although a very experienced pilot improved training would have resulted in him undertaking an engine-off landing. However, a drag chute or inflatable fin would have aided the pilot and given additional reassurance in the aircraft’s stability in autorotation without the TR functioning. A variable cambered fin which off-loaded the TR in cruising flight would have enabled the pilot to continue the flight to Blackbush and undertake a power-off landing or a higher speed run-on landing. A twin TR system would have provided redundancy although the second TRDS could have been damaged.</td></tr>
</table>

8.2 Occurrence No. 16 (failure of a TR drive shaft Thomas coupling)

8.2.1 **Key details**: see Table A-32:

Table A-32 Occurrence No. 16 (failure of a TR drive shaft Thomas coupling) - key details

Aircraft type/registration:	Puma HC1 XW215
Date and time:	22 October 1983
Location:	Hamelyn
Operator/type of flight:	RAF
Injuries:	None
Nature of damage:	Category 3 damage
Information source:	IFS(RAF)

8.2.2 **History of the flight**: As the aircraft was approaching the landing site, both the pilot and crewman heard a loud mechanical thump followed by a rumbling from the rear of the aircraft. The aircraft started to yaw left. Initially applying right pedal had a little effect but this quickly disappeared and the rate of yaw to the left increased.

As the aircraft continued to yaw the engines were shut down using the fuel shut-off levers. The aircraft hit the ground still rotating. The pilot transmitted a MAYDAY call, switched off the electrics using the emergency cut off bar, applied the rotor brake and followed the crewman out of the aircraft.

8.2.3 **Findings of the accident investigation**: The cause of the occurrence was assessed to be a failure of the intermediate gearbox input flexible coupling. This connecting flexible coupling to gearbox input flange was found to have split pins missing.

The aircraft tail boom was buckled and twisted and the TR blades were scraped and distorted. The fuselage skin on the starboard side rear of the crew door was badly ripped and rivets pulled. The starboard landing gear had collapsed and the nose leg was also damaged.

8.2.4 **Analysis**: see Table A-33:

Table A-33 Occurrence No. 16 (failure of a TR drive shaft Thomas coupling) - analysis

Occurrence information					
Failure mode:	TR drive shaft Thomas coupling failure				
Phase of flight:	Unknown				
Consequence:	Category 3 damage				
Pilot information and response					
Warning:	None				
Diagnosis:	The pilot was aware of a loss of yaw control.				
Action:	The pilot probably did the best he could in the circumstances.				
Effect:	Unavoidable damage to the aircraft.				
Possible impact of HUMS prevention and mitigation technologies					
Warning:	Vibration monitoring might have detected the missing spilt pins.				
Diagnosis:	TR rotational speed monitoring could have indicated a loss of TR drive to the pilot but there was insufficient time for the pilot to make use of this information.				
Action prompt:	The pilot required no prompting on the action to take.				
Effect:	A HUMS might have prevented the occurrence, but could not have affected the outcome once the failure had occurred.				
Application of non-HUMS prevention and mitigation technologies					
Technologies applicable	DC	IF	SBU	FBW	SLP
	HYD	SRU	BUCS	AFCS	ECS
	DF	**TTDD**	VCF	CNR	RSDS
Comment	Because of the short duration between failure and ground contact it is doubtful that deployment of a drag chute of inflatable fin would have produced any significant reduction in yaw as the rates were low. Because of the low forward speed a variable cambered fin would have been producing very little lift and therefore off-loading. A twin TR system would have provided redundancy although the second TRDS/ ITRGB could have been damaged.				

9 Failure of a TR drive shaft tail fold disconnect coupling

9.1 Occurrence No. 17 (failure of a TR drive shaft tail fold disconnect coupling)

9.1.1 Key details: see Table A-34:

Table A-34 Occurrence No. 17 (failure of a TR drive shaft tail fold disconnect coupling) – key details

Aircraft type/registration:	Sea King HAS Mk1
Date and time:	22 July 1974
Location:	Mull of Kintyre
Operator/type of flight:	RN
Injuries:	Minor/none
Nature of damage:	Unknown
Information source:	RN Accident Report No 3/74

9.1.2 **History of the flight**: The aircraft had been airborne for about one hour and was in level flight at 1000 feet, 110 knots IAS, when a grinding noise was heard from above the observer position.

The aircraft was headed towards the nearest point of land, and when an attempt was made to enter the hover an uncontrollable spin to the right immediately developed. The aircraft landed wheels up in a field and was shut down. The aircrew evacuated the aircraft through the cargo door and the co-pilot's window, having sustained very slight injuries.

9.1.3 **Findings of the accident investigation**: The occurrence was caused by failure of the TR drive shaft disconnect coupling. The disconnect coupling failed as a result of prolonged running in a misaligned condition.

9.1.4 **Analysis**: see Table A-35:

Table A-35 Occurrence No. 17 (failure of a TR drive shaft tail fold disconnect coupling) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">TR drive shaft tail fold disconnect coupling failure</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Unknown damage to aircraft</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Unknown - it is not known whether the coupling continued to transmit drive until the aircraft entered the hover, or whether drive had been lost before then.</td></tr>
<tr><td>Action:</td><td colspan="5">It is not possible to comment on the actions of the pilot.</td></tr>
<tr><td>Effect:</td><td colspan="5">It is not possible to comment on the effects of the pilot’s actions.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">Tail drive shaft vibration monitoring should have detected the misaligned disconnect coupling prior to the flight.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The information may have prevented the pilot from entering the hover and thereby losing control of the aircraft.</td></tr>
<tr><td>Effect:</td><td colspan="5">Tail drive shaft vibration monitoring should have prevented the occurrence. It is not possible to determine if a diagnosis of a loss of TR drive after the failure had occurred would have affected the outcome of the occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">It appears that the final TRDF occurred during the hover phase as the additional torque was demanded. There was very little time between failure and ground contact, however the use of a drag chute of inflatable fin might have reduced the rotation rate which developed as the torque was applied for the landing. There would have been no benefit from a variable camber fin in the hover. A twin TR system would have provided redundancy and prevented the accident.</td></tr>
</table>

10 Failure of a TR drive shaft hanger bearing

10.1 Occurrence No. 18 (failure of a TR drive shaft hanger bearing)

10.1.1 **Key details**: see Table A-36:

Table A-36 Occurrence No. 18 (failure of a TR drive shaft hanger bearing) - key details

Aircraft type/registration:	Bell 412 N3909F
Date and time:	26 August 1991
Location:	Gulf of Mexico
Operator/type of flight:	Public transport
Injuries:	1 fatality, 4 serious injuries
Nature of damage:	Unknown
Information source:	NTSB summary FTW91FA155

10.1.2 **History of the flight**: The helicopter was on final approach to an oil rig in the Gulf of Mexico when TR authority and directional control were lost. As the crew began an autorotation to the water the helicopter spun out of control to the right. It made 2 to 3 revolutions and impacted the water.

The right floatation gear deployed but the left floatation gear did not deploy because the pneumatic lines were pulled apart during impact. The helicopter rolled over and one passenger, who was incapacitated due to injury, was drowned.

10.1.3 **Findings of the accident investigation**: An investigation revealed that the TR drive shaft No 1 hanger bearing had overheated and disintegrated at an extremely high temperature. This had resulted in a failure of the TR drive shaft. The reason for the hanger bearing failure was not determined.

10.1.4 **Analysis**: see Table A-37:

Table A-37 Occurrence No. 18 (failure of a TR drive shaft hanger bearing) - analysis

<table>
<tr><th colspan="6">Occurrence information</th></tr>
<tr><td>Failure mode:</td><td colspan="5">TR drive shaft tail hanger bearing and shaft failure</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Final approach</td></tr>
<tr><td>Consequence:</td><td colspan="5">Fatal occurrence</td></tr>
<tr><th colspan="6">Pilot information and response</th></tr>
<tr><td>Warning:</td><td colspan="5">None reported</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The crew apparently diagnosed a loss of TR authority following the TR drive shaft failure.</td></tr>
<tr><td>Action:</td><td colspan="5">The crew attempted to enter autorotation but, for an unknown reason, lost control of the aircraft.</td></tr>
<tr><td>Effect:</td><td colspan="5">The helicopter impacted the water hard.</td></tr>
<tr><th colspan="6">Possible impact of HUMS prevention and mitigation technologies</th></tr>
<tr><td>Warning:</td><td colspan="5">Tail drive shaft hanger bearing vibration or temperature monitoring should have detected the bearing failure to possibly give a warning prior to the flight and certainly during the flight.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot but it is not known if there was sufficient time for the pilot to make use of this information.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The information would probably not have prompted the crew to do anything different.</td></tr>
<tr><td>Effect:</td><td colspan="5">Vibration monitoring should have prevented the occurrence. It is unlikely that a diagnosis of the loss of TR drive would have affected the outcome of the occurrence.</td></tr>
<tr><th colspan="6">Application of non-HUMS prevention and mitigation technologies</th></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">A drag chute or inflatable fin would have enabled the pilot to retain control in the autorotation following the failure of the drive shaft. The chute and fin would have also enabled a power speed combination to be achieved which might have allowed the aircraft to divert to a suitable landing site or assisted the pilot in maintaining control during a ditching. A variable cambered fin would have off-loaded the TR in forward flight and as a consequence the loss of TR thrust would have had little impact on controllability of the helicopter in the cruise. However, a run-on landing or engine-off landing would have been required, necessitating a return to a suitable landing site. A twin TR system would have provided redundancy and prevented the accident.</td></tr>
</table>

11 Failure of an intermediate or TR gearbox

11.1 Occurrence No. 19 (failure of an intermediate or TR gearbox)

11.1.1 **Key details**: see Table A-38:

Table A-38 Occurrence No. 19 (failure of an intermediate or TR gearbox) - key details

Aircraft type/registration:	Lynx AH Mk1 XZ204
Date and time:	18 March 1987
Location:	Near Soest, Germany
Operator/type of flight:	AAC
Injuries:	2 fatalities
Nature of damage:	Aircraft destroyed
Information source:	AAC Accident Report

11.1.2 **Crash site scene**: The aircraft had impacted on the boundary of two rear gardens in a village, straddling a hedge and a chain link fence. It was evident that the aircraft had impacted severely nose-down at a high vertical speed, but with little forward speed.

The tail boom had broken away from the main structure. All TR blades were intact and bore no evidence of any rotational impact damage. The upper end of the drive shaft was extensively damaged and the shaft had failed about mid way along its length.

11.1.3 **Findings of the accident investigation**: The occurrence was caused by a failure of the TRGB. The oil level sight glass was heavily stained. The gearbox was found to contain only 0.16 litres of oil, the required oil content is 0.9 litres. This was less than required for continued splash lubrication, the inevitable consequence of operation at this level was TRGB failure.

It appeared that the lack of oil was due to a cumulative servicing error, with many individuals mistaking the oil stain on the glass as the indicated oil level. The last recorded oil replenishment of the TRGB was some 108 airframe hours prior to the event. The last magnetic plug check was only 0.7 hours prior to the last flight; as far as is known there was no debris found at that time. After that inspection the aircraft completed approximately one hours ground running, spread over three separate occasions. The probability that, due to the 'tail down' attitude of the aircraft whilst on the ground, the oil which was present was to the rear of the gearbox and unlikely to lubricate the input bearing must be quite high.

The failure of the TRGB input bearing, and subsequently the internal gearing, may well have started prior to the final departure of the aircraft on this last sortie. It was concluded that the TRGB failed as a result of insufficient lubrication over an undetermined period.

11.1.4 **Analysis**: see Table A-39:

Table A-39 Occurrence No. 19 (failure of an intermediate or TR gearbox) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">TR gearbox failure</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Unknown</td></tr>
<tr><td>Consequence:</td><td colspan="5">Fatal occurrence</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">Unknown</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Unknown</td></tr>
<tr><td>Action:</td><td colspan="5">Unknown</td></tr>
<tr><td>Effect:</td><td colspan="5">Aircraft crashed</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">Vibration (and temperature) monitoring of the TR gearbox should have detected a lack lubrication of the gearbox components. Gearbox oil level sensing could also have provided a low oil level warning.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Owing to the lack of yaw stability of the Lynx, it is unlikely that any failure diagnostic information would have aided the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot would probably have been unable to respond any differently based on HUMS diagnostic information.</td></tr>
<tr><td>Effect:</td><td colspan="5">Vibration (and temperature) monitoring of the TR gearbox, or gearbox oil level sensing, may have prevented the occurrence. It is not possible to definitely claim that the occurrence could have been prevented without a HUMS cockpit warning capability as the investigation report stated that the period in which there was a lack of lubrication was undetermined. Post failure diagnostic information would have been unlikely to affect the outcome of the occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Assuming that the pilot had sufficient time to analyse the failure and operate the drag chute or inflatable fin, control of the aircraft could have been maintained enabling the crew to undertake an engine-off landing. A variable cambered fin would have off-loaded the TR in the cruise therefore failure of the tail drive would have had little impact upon the aircraft trim condition; The landing would have required a power-off landing. An in-line ducted fan would not have a TRGB and therefore not suffered the failure. A twin TR system would have provided redundancy and prevented the accident.</td></tr>
</table>

11.2 Occurrence No. 20 (failure of an intermediate or TR gearbox)

11.2.1 **Key details**: see Table A-40:

Table A-40 Occurrence No. 20 (failure of an intermediate or TR gearbox) - key details

Aircraft type/registration:	Bell B205A-1 C-FJTF
Date and time:	24 September 1993 at 1400 hours
Location:	Alberta, Canada
Operator/type of flight:	Underslung load work
Injuries:	1 serious injury
Nature of damage:	Substantial damage to aircraft
Information source:	Transportation Safety Board of Canada Report

11.2.2 **History of the flight**: The helicopter was carrying a sling load. When climbing at a height of approximately 200 feet the helicopter developed a severe vibration.

As the pilot attempted to set the load down, the helicopter began to pitch violently and rotate as it descended. The pilot was thrown about in his lap-belt, and was not able to operate the load release mechanism. The helicopter descended to the ground and came to rest on its left side with the load still attached to the helicopter. The pilot sustained serious chest injuries.

11.2.3 **Findings of the accident investigation**: On-site examination of the helicopter determined that the 42° gearbox in the TR drive train had failed. Failure analysis of the input bevel gear determined that it had fractured and failed due to relatively high-cycle, low-stress fatigue. Fatigue cracking had initiated at a root fillet on the concave face or drive side of a tooth.

It was concluded that the pilot lost TR authority because the input bevel gear of the 42° intermediate gearbox fractured due to a high-cycle, low stress fatigue mode of progressive cracking, disconnecting the drive shaft power from the main transmission to the TR.

11.2.4 **Analysis**: see Table A-41:

Table A-41 Occurrence No. 20 (failure of an intermediate or TR gearbox) - analysis

<table>
<tr><th colspan="6">Occurrence information</th></tr>
<tr><td>Failure mode:</td><td colspan="5">42° gearbox failure</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Climbing with a sling load</td></tr>
<tr><td>Consequence:</td><td colspan="5">Serious injury to pilot</td></tr>
<tr><th colspan="6">Pilot information and response</th></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Unknown</td></tr>
<tr><td>Action:</td><td colspan="5">Pilot attempted to set the load down; his actions were hampered by the aircraft's motion.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft landed heavily and rolled over with the load still attached.</td></tr>
<tr><th colspan="6">Possible impact of HUMS prevention and mitigation technologies</th></tr>
<tr><td>Warning:</td><td colspan="5">Gearbox vibration monitoring should have detected the gear fatigue crack prior to the flight.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot but there was insufficient time for the pilot to make use of this information.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot would not have been assisted by any additional information.</td></tr>
<tr><td>Effect:</td><td colspan="5">HUMS warning information should have prevented this occurrence, but post failure diagnostic information would not have affected the outcome of the occurrence.</td></tr>
<tr><th colspan="6">Application of non-HUMS prevention and mitigation technologies</th></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">The drag chute would have reduced the violent motions, however the final outcome would have been the same. An inflatable fin would have helped to damp the yaw rotation but would not have aided in pitch control and, again, the final outcome would have been the same. An in-line ducted fan would not have an ITRGB and therefore not suffered the failure. A twin TR system would have provided redundancy and prevented the accident.</td></tr>
</table>

11.3 Occurrence No. 21 (failure of an intermediate or TR gearbox)

11.3.1 **Key details**: see Table A-42:

Table A-42 Occurrence No. 21 (failure of an intermediate or TR gearbox) - key details

Aircraft type/registration:	AS355F1 Ecureuil II G-SASU
Date and time:	24 September 1994 at 1620 hours
Location:	Stapleford Tawney Aerodrome, Essex
Operator/type of flight:	Air test
Injuries:	None
Nature of damage:	Substantial damage to lower fin and left skid
Information source:	AAIB Bulletin No 11/94

11.3.2 **History of the flight**: Following scheduled servicing, engine ground runs lasting approximately 10 minutes had been carried out before making an airborne power check. The commander boarded the helicopter together with a mechanic and the licensed engineer in charge of its servicing.

The engines started normally and nothing abnormal was noticed as the helicopter was prepared for flight. The commander then hover-taxied the helicopter about 100 metres to a runway with the intention of transitioning to forward flight along the runway. However, whilst in the hover at about eight feet above the ground and just as he was about to begin the transition, the TR gearbox chip warning light illuminated.

The commander was in the process of explaining the associated Flight Manual guidance to the engineer when, within 2 or 3 seconds of the light illuminating, the helicopter started to yaw to the left and roll violently to the right. Initially, 'for a split second', the commander thought that the motion was caused by a gust but he rapidly realised he had full right pedal applied and diagnosed a TRDF.

Using large cyclic inputs to regain a reasonably level attitude whilst the helicopter yawed, the commander was able to land it on its skids within about one complete rotation. After touchdown, the helicopter continued to rotate and 'padded' from one skid to the other. The 'padding' stopped after the speed-select and fuel cut-off levers had been closed.

11.3.3 **Findings of the accident investigation**: A strip inspection of the TR gearbox revealed that the aft pinion bearing had overheated, its rollers had seized on the bearing outer race which subsequently had spun in its housing. This had resulted in the light alloy bearing housing becoming semi-molten around the bearing, destroying its location and allowing the pinion to disengage from its mesh with the output crown wheel. The resultant tooth 'skipping' which had occurred between the crown wheel and pinion had generated a great deal of swarf and heated the pinion to the point where the metal of the teeth had flowed to form a toothless cone. It is possible that the failure was caused by a lack of oil in the TR gearbox.

The manufacturer's Flight Manual listed the fault indicated by the TR gearbox chip detector warning light as 'Metal particles in the TGB oil' and gave the corresponding pilot action as 'Continue the flight – avoid prolonged hover flights'.

11.3.4 **Analysis**: see Table A-43:

Table A-43 Occurrence No. 21 (failure of an intermediate or TR gearbox) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">TR gearbox failure</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Hover-taxiing</td></tr>
<tr><td>Consequence:</td><td colspan="5">Damage to aircraft</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">TR gearbox chip warning 2 or 3 seconds before the failure.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot rapidly diagnosed a TRDF.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot was able to control and land the helicopter.</td></tr>
<tr><td>Effect:</td><td colspan="5">Damage to the aircraft was limited as far as possible.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">TR gearbox vibration monitoring could have detected the gearbox damage, but it is not possible to say whether this would have given an earlier indication than the chip detector. If the failure was caused by a lack of gearbox oil, gearbox oil level sensing could have provided a warning of this, however the lack of gearbox oil was not proven.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">TR rotational speed monitoring could have indicated a loss of TR drive to the pilot but there was insufficient time for the pilot to make use of this information.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot would not have been assisted by any additional information.</td></tr>
<tr><td>Effect:</td><td colspan="5">Gearbox oil level sensing might have prevented this occurrence if it was caused by a lack of gearbox oil; post failure diagnostic information would not have affected the outcome of the occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>**DF**</td><td>**TTDD**</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">The short duration between failure and ground contact precluded the use of deployable devices. An in-line ducted fan would not have a TRGB and therefore not suffered the failure. A twin TR system would have provided redundancy and prevented the accident.</td></tr>
</table>

12 Failure of TR hub components

12.1 Occurrence No. 22 (failure of TR hub components)

12.1.1 **Key details**: see Table A-44:

Table A-44 Occurrence No. 22 (failure of TR hub components) - key details

Aircraft type/registration:	AS332L Super Puma G-PUMH
Date and time:	27 September 1995 at 0730 hours
Location:	North Sea
Operator/type of flight:	Public transport
Injuries:	None
Nature of damage:	Minor
Information source:	AAIB Aircraft Incident Report No 2/98

12.1.2 **History of the flight**: The helicopter departed Aberdeen at 0702 hours for a flight to the Tiffany platform. At 0729 hours, whilst cruising at 3,000 feet AMSL, 120 knots, there was a sudden onset of severe airframe vibration.

The commander reported "major vibration" and requested an immediate return to Aberdeen, but subsequently decided to divert to Longside, near Peterhead. The aircraft descended to 2,000 feet with a speed of about 90 knots. Both crew thought that the vibration was associated with the MR and the commander decided to carry out a frequency adaptor drill. The helicopter was slowly descending through 1,800 feet. The handing pilot made several small pitch adjustments in an attempt to find a setting which reduced the level of vibration, however this appeared to make little difference. The crew then reviewed the situation and commented that the vibration appeared to be constant.

The commander reviewed the landing/ditching advice given in the drill. This recommended that, on land, the passengers should disembark from a low hover with the wheels held lightly on the surface. The aircraft descended to 1,000 feet and then continued at this height to Longside, with an airspeed of 65-85 knots.

Although the crew remained convinced that the vibration was emanating from the MR, the symptoms were confusing and they were not able to positively identify the source. The commander considered the vibration period to be nearer to 4R than 1R. The MR tracking was normal. The general airframe vibration was severe, but there was no obvious lateral component.

AT 0752 hours, the commander decided that the level of vibration had increased and accordingly upgraded the state of emergency to distress (MAYDAY).

The commander briefed the passengers on the planned evacuation procedure; his intention was to establish in a low hover with the wheels touching the ground. He asked them to leave ‘one at a time’ in order to make it easier for the handling pilot to maintain lateral balance. Unfortunately the public address system had become unserviceable due to the vibration levels and the briefing was not heard. The commander realised this and asked Longside to instruct the emergency services to open the left door and initiate the evacuation. The helicopter was established in a low hover and the passengers were evacuated without injury. The helicopter subsequently landed and was shut down at 0821 hours.

12.1.3 **Findings of the accident investigation**: The TR gearbox was examined and it was observed that the flapping hinge retainer at the Blue blade position had fractured on one side in the plane of the greasing point and had opened up, under centrifugal loads, by approximately 6-7 mm. Damage to the flap stop fitting in the blade spindle assembly was noted. This was due to repeated hard engagement with the integral flap stop.

The fatigue crack had propagated a maximum distance of some 60 mm from the origin before the remaining material failed in a ductile failure mode. Over 200 load cycles had been required for the crack to propagate to failure. Since the major loading was due to centrifugal forces, it was concluded that one fatigue cycle had occurred for each startup-shutdown cycle.

The evidence indicated that at some time in the life of the shaft the Blue blade flap bearing became stiff and initiated fatigue cracking, assisted by fretting and corrosion, within the bore. When the crack had reached approximately 50 mm in length it would have started to open up significantly under centrifugal loads, causing an increased vibration which was apparent in the IHUMS traces. It is likely that with the aircraft shut down and the centrifugal loads removed, the crack would have 'closed-up' again. During this period two 500 hour inspections and some balancing operations were carried out, but the crack was not detected. At the last rebalancing, the effect of the undetected crack was eliminated by increasing weights on the opposite blades.

During the subject flight, the crack progressed to such a length that the remaining material fractured in ductile overload. This caused the crack to open up by some 6mm due to plastic deformation, giving rise to severe vibration in the plane of the TR. This was the first event perceived by the crew.

Final separation of the fracture face and the onset of severe vibration occurred about 27 minutes into the incident flight. The last significant opportunity to detect the crack occurred some 287 hours before the incident when the previous 500 hour check had been carried out. This check specifically required an inspection for cracks in the TR shaft. The crack was probably approximately one inch in length at that time.

12.1.4 **The IHUM System**: The IHUMS completes a full cycle of transmission vibration measurements every flight hour. The data is acquired in the air but analysed on the ground. The IHUMS generated a clear increasing TR 1R vibration trend over some 50 flight hours, together with an exceedance alert of a predetermined threshold prior to the incident. However three data management issues arose that compromised its effectiveness in preventing this TR:

- The IHUMS did not provide for data to be automatically examined for developing trends as a routine.
- The specified alert threshold was, with hindsight, set too high.
- Specific maintenance actions relating the alert to the potential failure modes and the most relevant inspection methods did not exist.

As a result, the associated alert was not timely in relation to the damage progression and the engineer involved received no direct advice as to the location, or nature, of the defect.

The IHUMS generated an alert 5 days before the incident. The IHUMS indications were attributed by the engineer involved to slight 'free play' in the TR gearbox shaft bearings. The vibration was temporarily resolved by rebalancing.

12.1.5 **Conclusions:**

- The crew misidentified the source of the vibration. The commander's decision to continue the flight was reasonable in the light of the information available to the crew, but could have resulted in a critical loss of control had the TR gearbox detached.
- The IHUMS had recorded trend data which began to identify a developing vibration problem some 50 hours previously, culminating in an associated exceedance alert some 5 hours before the incident.
- Maintenance activity to identify the cause of the TR vibration problem failed to identify the cracked retainer.
- The ground based element of the IHUMS required operator intervention for the detection or plotting of trend data on an individual aircraft, and no such facility was available to facilitate comparison of a specific aircraft with the fleet as a whole.

12.1.6 **Analysis**: see Table A-45:

Table A-45 Occurrence No. 22 (failure of TR hub components) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of a TR blade flapping hinge retainer</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Diversion</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The crew failed to diagnose the source of the severe vibration.</td></tr>
<tr><td>Action:</td><td colspan="5">The crew diverted to the nearest land whereas the most appropriate action in the circumstances may have been to ditch. Disembarking passengers in a low hover placed a high load on the TR and exposed lives to unnecessary risk.</td></tr>
<tr><td>Effect:</td><td colspan="5">The helicopter landed safely but, had a TR blade been lost, the result could have been a fatal occurrence.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">The aircraft's HUMS vibration monitoring function did provide a valid warning of the failure, but the maintenance actions taken failed to detect the flapping hinge retainer crack.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">An on demand vibration check or continuous rotor vibration monitoring could have identified the TR as the source of the severe vibration and given information as to whether this was constant or increasing.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">Identification of the TR problem may have led the crew to ditch the aircraft, and would have prevented the disembarking of passengers in a low hover.</td></tr>
<tr><td>Effect:</td><td colspan="5">The HUMS should have prevented the incident, however this example demonstrates that the ability of HUMS to prevent occurrences is highly dependent on maintenance personnel understanding the significance of HUMS warnings and responding correctly to these. Once the failure had occurred a diagnosis of the source of the severe vibration would have greatly assisted the crew and would have enabled them to minimise risk to life.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Deployable devices, such as the drag chute and inflatable fin would not have been used because the pilot was unable to diagnose the problem. A variable cambered fin used to off-load the TR in forward flight would have reduced the loading on the TR and possibly masked the fault until hover. Similarly, in the event of complete failure of one rotor, a twin TR solution, would have enabled the helicopter to continue in flight. This assumes that TR components from the failed hub did not impact with the MR or duct causing catastrophic damage to the helicopter.</td></tr>
</table>

12.2 **Occurrence No. 23 (failure of TR hub components)**

12.2.1 **Key details**: see Table A-46:

Table A-46 Occurrence No. 23 (failure of TR hub components) - key details

Aircraft type/registration:	Bell 214ST G-BKJD
Date and time:	2 October 1991 at 1010 hours
Location:	81 nm east of Aberdeen
Operator/type of flight:	Public transport
Injuries:	None
Nature of damage:	Minor
Information source:	AAIB Bulletin No 1/92

12.2.2 **History of the flight**: The helicopter had departed from the Maersk Highlander platform at 0836 hours on a flight to Aberdeen when, some 34 minutes later and at 2,500 feet, a severe high frequency vibration was felt and heard.

The commander immediately initiated a gentle descent, whilst reducing the speed to 80 knots, and made a PAN call declaring his intent to seek an immediate diversion. Although the vibration was still severe at 80 knots, it had reduced slightly and the helicopter was fully controllable in level flight. The commander identified "Kittiwake", which was only 12 nm behind, as the closest suitable landing deck and turned towards it.

When inbound to Kittiwake at a range of 1 nm, a low speed handling check was carried out and confirmed that they still had TR control. Although the vibration level had increased slightly, the descent was continued to an uneventful touchdown on the deck. Following disembarkation of the passengers it was noticed that, during the shutdown, the amplitude of the vibration increased significantly before ceasing as the rotors stopped.

12.2.3 **Findings of the accident investigation**: Subsequent inspection revealed that one of the two TR counterbalance weight bellcrank assemblies was missing from the helicopter and that in separating it had struck the blade grips and the blade surface of one of the TR blades.

The primary purpose of the counterweights is to reduce the steady loads in the yaw control system produced by the centrifugal pitching moment of the TRs, thereby permitting operation in the event of hydraulic servo failure. The two counterweight bellcranks are mounted on lugs, or journals, positioned at 90° relative to the pitch link lugs. The failure had occurred in a machined undercut at the base of one of the journals. It was found that the fracture area consisted of a 50% division between fatigue and fast fracture.

12.3 **Analysis**: see Table A-47:

Table A-47 Occurrence No. 23 (failure of TR hub components) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of a TR counterbalance weight bellcrank assembly</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Diversion</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">It is unclear as to whether the pilot correctly identified the source of the vibration, a handling check confirmed that he still had TR control.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot diverted to the nearest suitable landing platform.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft landed successfully.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">None possible as the crack was not in the drive load path; there would be no change in vibration until there was a change in mass balance as a result of the loss of the counterweight.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">An on demand vibration check or continuous rotor vibration monitoring would have confirmed that the TR was the source of the vibration and also provided information on the severity of this vibration, and whether it was increasing.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">It is unclear as to whether the pilot would have behaved differently if additional information was available.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS would probably not have affected what was a satisfactory outcome of the event.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Deployable devices, such as the drag chute and inflatable fin might not have been used since it is unclear whether the pilot was able to diagnose the problem. A variable cambered fin used to off-load the TR in forward flight would have reduced the loading on the TR and possibly masked the fault until hover. Similarly, in the event of complete failure of one rotor, a twin TR solution, would have enabled the helicopter to continue in flight. This assumes that TR components from the failed hub did not impact with the MR or duct causing catastrophic damage to the helicopter.</td></tr>
</table>

13 TR blade failure

13.1 Occurrence No. 24 (TR blade failure)

13.1.1 **Key details**: see Table A-48:

Table A-48 Occurrence No. 24 (TR blade failure) - key details

Aircraft type/registration:	MD 500E
Date and time:	30 April 1992
Location:	Mount Zion, Kentucky
Operator/type of flight:	Unknown
Injuries:	None
Nature of damage:	Separation of the TR assembly
Information source:	NTSB Id NYC92GA089

13.1.2 **History of the flight**: While flying in the cruise configuration at 1,500 feet AMSL, and about 10 minutes into the flight, the helicopter started to vibrate. The pilot elected to make a forced landing in the most suitable area available. During the descent the vibration continued to worsen. At about 5 feet above the selected landing site the pilot heard a loud bang, the helicopter yawed to the right and pitched nose-down. The pilot lowered the collective and put the helicopter on the ground.

13.1.3 **Findings of the accident investigation**: The loss of the abrasion strip from the leading edge of a TR blade induced vibrational stresses that were high enough to initiate fatigue failure in the TR gearbox mounting studs. This resulted in the in-flight separation of the TR gearbox assembly from the helicopter.

13.1.4 **Analysis**: see Table A-49:

Table A-49 Occurrence No. 24 (TR blade failure) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Loss of a TR blade abrasion strip</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">In-flight separation of the TR assembly</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot correctly identified a vibration problem.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot made a forced landing.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft landed immediately after loosing the TR assembly.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">An on demand vibration check or continuous rotor vibration monitoring could have indicated the severity of the vibration, but this would probably not have helped the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot would not have been prompted to take any different action.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS would not have affected the outcome of this occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Deployable devices, such as the drag chute and inflatable fin might not have been used since it is unclear whether the pilot was able to diagnose the problem. An off-loaded TR using a variable cambered fin would have reduced the thrust required and therefore TR pitch requirements. As a consequence the out of balance forces due to the out of track blade would have been reduced. This might have reduced the fatigue damage to the gearbox feet. A twin TR system would have provided redundancy and, unless damaged by detachment of the first TRGB, would have prevented the final loss of control.</td></tr>
</table>

14 TR pitch control system seized/jammed

14.1 Occurrence No. 25 (TR pitch control system seized/jammed)

14.1.1 **Key details**: see Table A-50:

Table A-50 Occurrence No. 25 (TR pitch control system seized/jammed) - key details

Aircraft type/registration:	Lynx XZ605
Date and time:	20 February 1989
Location:	Fagernes Airport, Norway
Operator/type of flight:	AAC
Injuries:	None
Nature of damage:	Category 4 damage
Information source:	AAC Accident Report

14.1.2 **History of the flight**: The aircraft was to undertake a night flying training sortie with a student and instructor from an airfield. As the student lifted the aircraft into the hover it yawed to the right. The student could not correct the yaw and the instructor took control. He discovered a restriction in the yaw pedals and applied considerable force to the left pedal which he felt move forward but this did not reduce the rate of yaw.

Realising he has a TR control or drive problem he elected to climb and manoeuvre the aircraft away from a fuel tank and other aircraft. At 30-40 feet and approximately the maximum permissible rate of yaw he instructed the student to retard both engine control levers and carried out a heavy landing into snow with negligible forward speed or yaw. The aircraft bellied on the snow in an upright position, the crew sustained no injuries.

14.1.3 **Findings of the accident investigation**: Examination of the aircraft controls revealed that the starboard yaw pedals control lock was still fitted and that the port, outboard yaw pedal, had rotated approximately 40° forward about its pedestal mounting. This was caused by the instructor attempting to apply left pedal on take-off to correct the yaw to starboard whilst the yaw pedals lock was fitted. The aircraft had become airborne with the starboard yaw pedals control lock fitted.

14.1.4 **Analysis:** see Table A-51:

Table A-51 Occurrence No. 25 (TR pitch control system seized/jammed) - analysis

Occurrence information					
Failure mode:	The starboard yaw pedals control lock was still fitted				
Phase of flight:	Take off				
Consequence:	Category 4 damage to the aircraft				
Pilot information and response					
Warning:	None. The pilot apparently did not check for full and free movement of the controls prior to take off.				
Diagnosis:	The pilot detected the restriction in the yaw pedals.				
Action:	Immediate and appropriate action was taken.				
Effect:	The consequences of the fault could not have been prevented.				
Possible impact of HUMS prevention and mitigation technologies					
Warning:	None possible				
Diagnosis:	None required				
Action prompt:	None required				
Effect:	A HUMS could not have affected the outcome of the occurrence.				
Application of non-HUMS prevention and mitigation technologies					
Technologies applicable	DC	IF	SBU	**FBW**	SLP
	HYD	SRU	BUCS	AFCS	ECS
	DF	TTDD	VCF	CNR	RSDS
Comment	These technologies would not have helped, however, a fly-by-wire system might not have required pedal locks or if fitted, a warning caption could have been generated on rotor start.				

15 TR pitch change mechanism failure

15.1 Occurrence No. 26 (TR pitch change mechanism failure)

15.1.1 **Key details**: see Table A-52:

Table A-52 Occurrence No. 26 (TR pitch change mechanism failure) - key details

Aircraft type/registration:	Lynx HAS 2 XZ249
Date and time:	4 May 1983
Location:	Gulf of Oman
Operator/type of flight:	RN
Injuries:	4 back injuries
Nature of damage:	Category 5 damage
Information source:	RN Accident Report No 2/83

15.1.2 **History of the flight**: The aircraft was returning to a ship after picking up a passenger. The pilot became aware that he was requiring a progressive displacement of the rudder pedals to the right to maintain straight flight. Some 6 to 8 minutes later the right pedal was fully forward, a gentle left hand turn was initiated. A bang was felt and the turn became uncontrollable.

An immediate descent was initiated and the engines shut down. The water impact was severe, the starboard flotation gear failed to operate and the aircraft rolled right. The occupants escaped with varying degrees of difficulty, all sustaining back injuries, and were recovered by boat.

15.1.3 **Findings of the accident investigation**: The occurrence was caused by a fatigue failure of the TR gearbox pitch change input lever, resulting in an irrecoverable, out of control flight regime.

The point of failure was beyond the control system stops, permitting the TR blades to adopt a more positive pitch than that permitted by design. The starboard flotation gear failed to operate because the wiring to it was disrupted during the impact.

15.1.4 **Analysis**: see Table A-53:

Table A-53 Occurrence No. 26 (TR pitch change mechanism failure) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of the TR gearbox pitch change input lever</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Some injuries and Category 5 damage to the aircraft.</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">The pilot had some 6 to 8 minutes problem warning prior to the final failure.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot realised that increasing right pedal was required to maintain straight flight and must have therefore been aware of some developing control problem.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot could do little after the final failure as the yaw power being applied was beyond that required for full collective lever position, therefore the aircraft was in an irrecoverable, out of control, flight regime.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft impacted the water hard and rolled over.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">Measuring the actual TR pitch (i.e. control output) and comparing this with the TR pedal position (i.e. control input) would have detected the developing problem. Alternatively, mapping of control inputs against key flight parameters and combining this with TR rotational speed monitoring could have detected a control problem prior to the final failure.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">It may have been possible to diagnose a TR control problem and indicate this to the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The pilot would probably not have acted differently with additional information available.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS would have been unlikely to affect the outcome of this occurrence. The pilot was already aware of the problem prior to the final failure and additional warning would probably not have changed the consequences of the failure.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Later marks of Lynx have a fail safe pitch condition achieved using the spring bias unit and reduced preponderance weights, whilst retaining manual reversion characteristics. If this aircraft had been fitted with this system it would have enabled the aircraft to return to the land base and undertake a run on landing at around 25 - 30 kn. A drag chute, inflatable fin and variable cambered fin used in forward flight to off load the TR would have also enabled the aircraft to be flown back to the land base for a powered run on landing. This failure occurred between the rotor and the jack therefore precluding the use of BUCS, AFCS and FBW. It is possible that a secondary load path would have avoided this occurrence as with twin rotor solutions, where only control of one rotor would have been lost. Use of main rotor speed control (via the Speed Select Lever) at constant power enables changes to be made to MR torque, which may have assisted the pilot to maintain some control.</td></tr>
</table>

15.2 **Occurrence No. 27 (TR pitch change mechanism failure)**

15.2.1 **Key details**: see Table A-54:

Table A-54 Occurrence No. 27 (TR pitch change mechanism failure) - key details

Aircraft type/registration:	Puma HC1 XW215
Date and time:	24 June 1991
Location:	North Sea
Operator/type of flight:	RAF
Injuries:	4 slight injuries
Nature of damage:	Category 4 damage
Information source:	D/IFS(RAF)/140/66/91/1

15.2.2 **History of the flight**: The helicopter was on a transition flight from RAF Manston to RAF Gutersloh. The aircraft took off at 1343 hours and was soon established in the cruise. When over the sea some 15 minutes after take off the crew experienced a marked high frequency vibration that grew in severity.

The pilot announced his intention to return to RAF Manston, and commenced a gentle descent (to level at approximately 300 feet AMSL) at 70 knots. Shortly after the aircraft rolled onto heading, the crew became aware of a slow rate of yaw to the left. The pilot progressively applied full right pedal to counter the yaw, immediately reduced collective pitch and lowered the aircraft nose to maintain airspeed. The autopilot was disengaged but this had no effect on the rate of yaw. He initially diagnosed the symptoms as those of a TRDF, but quickly assessed that the aircraft was not exhibiting the behaviour he would have expected from such a failure. There was a minimal amount of TR thrust which, although uncontrollable, was sufficient to keep the aircraft airborne for a little longer.

The Flight Reference Cards and Aircrew Manual gave no guidance for this type of failure. The pilot issued a MAYDAY, giving his position and intention to ditch. The aircraft was in a shallow left-hand spiral descent with the nose approximately 10° below the horizon. Attempting to diagnose the failure, the pilot ascertained that an increase in collective pitch increased the rate of yaw, whilst decreasing the collective pitch did not affect the yaw, although the rate of descent increased.

At 30 feet, with the aircraft in an ever tightening spiral and 15° nose-down attitude, the pilot instructed the crewman to retard the throttles. The rate of yaw to the left stopped immediately and the aircraft ditched at zero forward speed into wind, with all available collective pitch used to cushion the impact. The aircraft settled gently in the water, after the crew had left it slowly rolled inverted with a nose-down attitude but remained on the surface for some minutes before sinking.

15.2.3 **Findings of the accident investigation**: There was evidence that the TR was rotating correctly and that the problem was not caused by a loss of TR drive. The TR pitch change mechanism was examined and the spider sliding sleeve was found to have failed at the base of the TR spider. The TR control rod was also found to have failed in tension approximately one third of its length from the spider end.

The mode of failure of the spider sliding sleeve was identified as fatigue in bending followed by rapid ductile failure. Examination indicated rapid fracture propagation from high bending stress. Damage to the TR control rod took the form of severe abrasion and failure at a point within the spider sliding sleeve.

All the blade feathering hinges showed some sign of degradation, one blade hinge required considerably greater effort than the others to turn, indicating damage to the bearings. An adjacent blade was also stiff to turn. The effect of this increased friction would be to amplify the loads being transmitted through the pitch control rods to the spider arms and hence the spider sliding sleeve. The oscillating nature of these loads caused by the flapping motion of the blades provided the load reversals required to fatigue a component and led to the failure of the spider sliding sleeve.

Strip examination of the feathering hinge confirmed damage to the ball races. There was also a considerable amount of sand compacted at the base of the bearing sleeve. Sand was also suspended within the grease, acting effectively as grinding paste. Records showed that the aircraft had operated for 91 hours in the Gulf during Operation Granby.

Some 10 flying hours before the occurrence the aircraft had undergone vibration analysis as a result of the replacement of two MR blades. During the analysis a high 1T vibration was detected which required rectification in according with the Vibration Analysis Schedule. A table within the schedule provides a diagnostic aid chart which details various vibration characteristics along with possible causes. However, the schedule does not direct tradesmen to this chart but leads them to eliminate the vibration by checking for radial out of balance forces and countering them by the application or adjustment of balance weights. In this case the vibration was cured by the addition of 6 grammes to a blade. The investigators considered that reacting to unusual vibrations by automatically re-balancing could mask the root cause and possibly allow a potential failure condition to continue.

It was concluded that:

- The occurrence was caused by a loss of TR thrust, which was brought about by the failure of the TR control rod. This rod had failed under tension because of the abrasion it had been subjected to by the internal surface of the spider sliding sleeve following its failure.
- The sleeve had failed owing to fatigue as a result of the application of abnormal bending loads, generated by severely degraded feathering hinge bearings, which were transferred through the pitch change links.
- The rapid degradation of the feathering hinge bearings was brought about by the accumulative ingress of sand during operations in a desert environment. The degradation of the bearings occurred within a 200 hour bearing examination period.
- Simulator training contributed to the skilful and professional manner in which the pilot successfully handled a rare and complex emergency.

15.2.4 **Analysis**: see Table A-55:

Table A-55 Occurrence No. 27 (TR pitch change mechanism failure) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of the TR control rod</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Cruise flight</td></tr>
<tr><td>Consequence:</td><td colspan="5">Ditching</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">The pilot had some warning due to the apparently gradual onset of the failure.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot initially incorrectly diagnosed a TRDF; various control inputs were subsequently made to attempt to diagnose the actual failure.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot retained some control during the descent handled the aircraft well in the circumstances.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft was ditched successfully.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">TR vibration monitoring should have detected the TR bearing problems.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Comparing TR control inputs and outputs, or performing control input mapping together with TR rotational speed monitoring, it might have been possible to diagnose a TR control problem and indicate this to the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">It is not possible to determine whether the pilot would have acted differently with additional information available.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS should have prevented the occurrence, however once the failure had occurred it would probably not have affected the satisfactory outcome of the occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">If a fail-safe pitch setting had been designed into the TR system the pilot would have been able to fly to a suitable landing site and undertaken a run-on landing. A drag chute, inflatable fin and cambered fin would also have enabled the pilot to retain sufficient control to enable a run-on or engine-off landing.
A twin TR system would have provided some redundancy assuming that its TR blade feather bearings had not been similarly affected by sand contamination. Although reduction in MR torque was eventually achieved immediately prior to ditching, earlier achievement through MR speed control (via the throttles) was ruled out, since increase in this parameter is not possible for this helicopter type. The benefits of the other technologies would have been lost due to the failure resulting in loss of jack inputs.</td></tr>
</table>

15.3 **Occurrence No. 28 (TR pitch change mechanism failure)**

15.3.1 **Key details**: see Table A-56:

Table A-56 Occurrence No. 28 (TR pitch change mechanism failure) - key details

Aircraft type/registration:	Sea King HAS 2 XV665
Date and time:	20 January 1981
Location:	Gulf of Oman
Operator/type of flight:	RN
Injuries:	None
Nature of damage:	Category 4 damage
Information source:	RN Accident Report No 2/81

15.3.2 **History of the flight**: After transition away from the fourth dip of a Combined Anti-Submarine Exercise sortie, climbing through 150 ft at 60 knots, the aircraft yawed to starboard. Full left pedal was applied to no effect.

Fault diagnosis could not locate the problem, it was found that a heading could be maintained by applying 55% twin torque and flying ball left about 15° left wing low. Exploration of the flight envelope showed that a running landing ashore was not possible.

An autorotation was successfully carried out close to a ship. On ditching a blade struck the water and the aircraft rolled left and inverted. All the crew escaped and were picked up immediately. The starboard flotation bag did not inflate.

15.3.3 **Findings of the accident investigation**: The occurrence resulted from the failure of the Hyatt bearing (a thrust bearing on the pitch control shaft), the reason for the failure could not be determined. This occurrence was similar to 12 other failures on S61 type aircraft since 1973.

The failure of the flotation system to inflate fully was due to failure of the co-pilot to press the button fully home.

15.3.4 **Analysis**: see Table A-57:

Table A-57 Occurrence No. 28 (TR pitch change mechanism failure) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of a bearing in the TR pitch control mechanism</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Climbing at 150 feet</td></tr>
<tr><td>Consequence:</td><td colspan="5">Category 4 aircraft damage</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The crew diagnosed that a TRCF had occurred, and that there was a limited amount of pitch control, but not sufficient to make a safe power-on landing.</td></tr>
<tr><td>Action:</td><td colspan="5">Given the limited pitch control available and the location of the aircraft (in the Gulf of Oman) the pilot took the most appropriate action, which was to ditch the aircraft close to a ship.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft was ditched successfully.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">Vibration monitoring may have detected the Hyatt bearing failure, however there is insufficient evidence to definitely claim that an adequate warning could have been given.</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Comparing TR control inputs and outputs, or performing control input mapping with TR rotational speed monitoring, it might have been possible to diagnose a TR control problem and indicate this to the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The information would not have prompted the pilot to act any differently.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS may have prevented this occurrence</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">A fail-safe pitch setting would have enabled a run-on landing to be undertaken. The addition of a drag chute, inflatable fin or variable cambered fin would have also helped the pilot perform a shore based landing. The actual failure occurred at the Hyatt bearing, located inside the TR gearbox, which allows the stationary control inputs to be transferred to the rotating control pitch change levers. This failure would therefore not have benefited from FBW, BUCS and AFCS technologies. A twin TR system would have retained more TR thrust and reduced the loss of control. Use of main rotor speed control (via the Speed Select Lever vernier knobs or manual throttle levers) at constant power enables changes to be made to MR torque, which may have assisted the pilot in reducing the required sideslip.</td></tr>
</table>

15.4 Occurrence No. 29 (TR pitch change mechanism failure)

15.4.1 **Key details**: see Table A-58:

Table A-58 Occurrence No. 29 (TR pitch change mechanism failure) - key details

Aircraft type/registration:	Lynx
Date and time:	Unknown
Location:	RNAS Portland
Operator/type of flight:	RN
Injuries:	None
Nature of damage:	None
Information source:	1998 RN ‘Cockpit’ article

15.4.2 **History of the flight**: Having served on a committee to investigate and improve the advice given to aircrew in the event of TR malfunctions in a prior posting, the Squadron Air Engineering Officer (AEO) had given the aircrew a briefing on TRCF reactions.

Just over a month later an aircraft had undergone maintenance when, amongst other things, a new TR gearbox had been fitted. A check test flight was being carried out; the first check involved lifting into the hover. As the aircraft lifted there was a slight yaw to the right which the pilot compensated for, but by the time the aircraft was established in a 10 foot hover, a matter of only 2-3 seconds after launch, the aircraft was continuing to diverge to the right with full left pedal applied. The pilot called out “full left pedal”, and the aircraft accelerated into a right hand spot turn over which the aircrew had no control.

The aircrew recalled the AEO’s briefing and reduced the MR speed (which also reduces TR speed and thrust), the yaw accelerated further, exacerbated by the fact that they were entering the downwind arc. The words of the briefing were then recalled “right hand turn equals low power setting, therefore increase N_R”. The Speed Select Lever (SSL) was pushed forward to increase MR speed (and hence TR speed and thrust), the yaw rate slowed down. The aircrew regained control of the aircraft and were able to land without further incident. The aircraft had been airborne for a total of about 40 seconds.

15.4.3 **Findings of the accident investigation**: A subsequent examination of the TR gearbox revealed that the internal control rod had been incorrectly assembled, with the net result that there was a small amount of initial TR control, but this soon ran out.

In his lecture, AEO had dealt specifically with TR control malfunctions in the hover. The aircrew were convinced that it was this which prompted their reactions on the day of the incident.

15.4.4 **Analysis**: see Table A-59:

Table A-59 Occurrence No. 29 (TR pitch change mechanism failure) - analysis

<table>
<tr><th colspan="6">Occurrence information</th></tr>
<tr><td>Failure mode:</td><td colspan="5">Failure of the TR pitch control</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Hover</td></tr>
<tr><td>Consequence:</td><td colspan="5">Safe landing</td></tr>
<tr><th colspan="6">Pilot information and response</th></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilots correctly diagnosed a TRCF.</td></tr>
<tr><td>Action:</td><td colspan="5">Prompted by a briefing on TR malfunctions, the pilots regained control of the aircraft by increasing TR speed and hence thrust.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft was landed safely.</td></tr>
<tr><th colspan="6">Possible impact of HUMS prevention and mitigation technologies</th></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">Comparing TR control inputs and outputs, or performing control input mapping with TR rotational speed monitoring, it should have been possible to diagnose a TR control problem and indicate this to the pilot.</td></tr>
<tr><td>Action prompt:</td><td colspan="5">The information would not have prompted the pilots to act any differently.</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS would not have affected the satisfactory outcome of the incident.</td></tr>
<tr><th colspan="6">Application of non-HUMS prevention and mitigation technologies</th></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">Recent validated TR advice for the Lynx had been discussed by the crew shortly before the failure occurred. This information prompted the crew to use main rotor speed control (via the Speed Select Lever) at constant power, enabling changes to be made to MR torque, and regaining control. However, possible use of drag chute or inflatable fin would have aided the pilots in the recovery if validated TR advice had not been available. A twin TR system would have retained more TR thrust and reduced the loss of control. The control problem occurred through the incorrect assembly of the control rod through the TR gearbox which resulted in a small amount of initial TR control being available which soon ran out. Therefore the other technologies which operate via the TR jack would have had no benefit.</td></tr>
</table>

15.5 **Occurrence No. 30 (TR pitch change mechanism failure)**

15.5.1 **Key details**: see Table A-60:

Table A-60 Occurrence No. 30 (TR pitch change mechanism failure) - key details

Aircraft type/registration:	Lynx AH Mk7 XZ192
Date and time:	7 September 1996
Location:	Stafford
Operator/type of flight:	AAC
Injuries:	None
Nature of damage:	Category 4 damage
Information source:	AAC Accident Report

15.5.2 **History of the flight**: The aircraft was making a flight from Aldergrove to Thetford, involving a refuelling stop at RAF Stafford with six passengers. The handling pilot started his descent into Stafford for the refuelling stop. During the descent he noticed that the aircraft was yawing to the right and that he was having to apply a large amount of left TR pedal, although it was still not having a significant effect on maintaining directional control of the aircraft.

The aircraft commander commented on the amount of left pedal being used. He de-selected Lanes 1 and 2 Yaw Automatic Flight Control System (AFCS) channels and this appeared to allow limited yaw control and the aircraft straightened up. The aircraft commander took over control of the aircraft, electing to overshoot RAF Stafford and find a more suitable landing area away from any buildings. As he turned away the aircraft again yawed right and he applied cyclic cross control so that he was then able to 'crab' away from Stafford. He believed that he had an AFCS problem and he switched off the AFCS completely, leaving the aircraft in manual control. He still had to apply a large amount of cyclic cross control, and he then decided to carry out a double engine-off landing into a large field about 2 miles away.

Both engine control levers were pulled back at the appropriate time during the descent to close down both engines, the aircraft commander was then committed to carrying out a manual control run-on landing into the selected field. When the engines were cut the loss of torque reaction from the engines allowed the aircraft to straighten up just as the aircraft touched down, allowing a skids parallel, engine-off landing. The aircraft speed at touchdown was estimated by the aircrew to be about 50 knots. The aircraft slid along the ground and then rolled over.

15.5.3 **Findings of the accident investigation**: The TR gearbox magnetic plug was found lodged between the gearbox mounting and the tail pylon and on inspection there was an excessive amount of ferrous debris on the plug. This debris was later analysed as being roller bearing material. From the post occurrence examination carried out on the controls of the airframe and engines, it was determined that the occurrence was caused by the failure of the TR pitch control rod. The TR pitch control rod shaft fits into the inner part of the McGill bearing. The failure was apparently in this area.

The report references some experiments at GKN WHL intended to confirm whether there was a requirement for a thermocouple sensor on the shaft, an electronic chip detector or some form of oil temperature monitoring system.

15.5.4 **Analysis**: see Table A-61:

Table A-61 Occurrence No. 30 (TR pitch change mechanism failure) - analysis

Occurrence information					
Failure mode:	Failure of the TR pitch control rod				
Phase of flight:	Commencing a descent				
Consequence:	Category 4 damage to the aircraft				
Pilot information and response					
Warning:	None				
Diagnosis:	The crew were aware that they had a TR control malfunction, but apparently failed to diagnose the nature of the problem.				
Action:	After flying the aircraft to a suitable location, the pilot made an engine-off landing.				
Effect:	The aircraft made a run-on landing and rolled over.				
Possible impact of HUMS prevention and mitigation technologies					
Warning:	Vibration monitoring may have detected the McGill bearing failure, however there is insufficient evidence to definitely claim that an adequate warning could have been given.				
Diagnosis:	Comparing TR control inputs and outputs, or performing control input mapping with TR rotational speed monitoring, it should have been possible to diagnose a TR control problem and indicate this to the pilot.				
Action prompt:	The information would probably not have prompted the pilot to act any differently.				
Effect:	A HUMS may have prevented this occurrence.				
Application of non-HUMS prevention and mitigation technologies					
Technologies applicable	**DC**	**IF**	**SBU**	FBW	SLP
	HYD	SRU	BUCS	AFCS	ECS
	DF	**TTDD**	**VCF**	**CNR**	RSDS
Comment	The failure occurred in the McGill bearing in the centre of the gearbox which allows stationary to rotating control inputs to be made. Lynx Mk7 has a fail-safe pitch which should enable a run-on landing to be achieved, although in this incident it appears the ideal pitch was not achieved. However, the use of an inflatable fin, drag chute or variable cambered fin would have reduced the run-on landing speed considerably, greatly reducing pilot work load during the landing and would have possibly saved the aircraft from rolling over. A twin TR system would have retained more TR thrust and reduced the loss of control. Use of main rotor speed control (via the Speed Select Lever) at constant power enables changes to be made to MR torque, which may have assisted the pilot in reducing the required sideslip. The other technologies requiring inputs through the jack would not have worked.				

16 Loss of TR effectiveness

16.1 Occurrence No. 31 (loss of TR effectiveness)

16.1.1 **Key details**: see Table A-62:

Table A-62 Occurrence No. 31 (loss of TR effectiveness) - key details

Aircraft type/registration:	SA341G Gazelle 1 G-TURP
Date and time:	9 September 1991 at 0700 hours
Location:	Farm, Essex
Operator/type of flight:	Private
Injuries:	None
Nature of damage:	Aircraft damaged
Information source:	AAIB Bulletin No 1/92

16.1.2 **History of the flight**: The pilot completed pre take-off checks before lifting off with the intention of bringing the helicopter to a stable hover about six feet above the paved helipad. The All-Up Weight (AUW) was well below the maximum, the OAT was 10 °C and the wind strength was 2 knots.

As the aircraft became airborne it drifted sideways and yawed to the left. The pilot corrected with lateral cyclic and right pedal but the yaw rate increased. Despite the application of full right pedal, the aircraft continued to rotate to the left. There were no abnormal noises or vibrations and the collective lever was raised to a position appropriate for the conditions. After approximately two or three revolutions the pilot diagnosed TR and so, in accordance with the flight manual, he lowered the collective and accepted the ensuing rough landing back onto the helipad. The landing was heavy but with skids level.

16.1.3 **Findings of the accident investigation**: Examination of the helicopter revealed no evidence of any pre-occurrence failure or malfunction. The Gazelle has a history of suffering unexplained loss of fenestron effectiveness, commonly known as 'fenestron stall'. The majority of documented fenestron stalls have occurred in the hover during an attempted left turn in conditions of significant wind speed (10 knots +) from astern or from the right, but there have also been cases in a variety of other wind and flight conditions.

Recommended procedures for military operators following fenestron stall have included reducing right yaw pedal application until fenestron effectiveness is restored and then reapplying right pedal, attempting to shutdown the engine, and lowering the collective lever and accepting a heavy landing.

16.1.4 **Comment on the findings of the accident investigation**: In their response to the occurrence involving Gazelle G-HAVA, CAA disagreed with the military procedures to be adopted in the event of a loss of TR effectiveness in the Gazelle. Eurocopter trials suggested that the Fenestron has not stalled and that full right pedal application would eventually recover the situation. The problem for the pilot is to differentiate between a nose left rotation due to insufficient pedal begin applied, and the same symptoms due to a TRDF. CAA continue to instruct in the civil Flight Manual that the rapid nose left rotation should be diagnosed as TRDF and, from a hover, an immediate landing should be executed.

16.1.5 **Analysis**: see Table A-63:

Table A-63 Occurrence No. 31 (loss of TR effectiveness) - analysis

<table>
<tr><td colspan="6">Occurrence information</td></tr>
<tr><td>Failure mode:</td><td colspan="5">Loss of fenestron effectiveness</td></tr>
<tr><td>Phase of flight:</td><td colspan="5">Take off</td></tr>
<tr><td>Consequence:</td><td colspan="5">Damage to the aircraft</td></tr>
<tr><td colspan="6">Pilot information and response</td></tr>
<tr><td>Warning:</td><td colspan="5">None</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">The pilot did not correctly diagnose a fenestron stall.</td></tr>
<tr><td>Action:</td><td colspan="5">The pilot perhaps took the most appropriate action under the circumstances.</td></tr>
<tr><td>Effect:</td><td colspan="5">The aircraft landed heavily but remained upright.</td></tr>
<tr><td colspan="6">Possible impact of HUMS prevention and mitigation technologies</td></tr>
<tr><td>Warning:</td><td colspan="5">None possible</td></tr>
<tr><td>Diagnosis:</td><td colspan="5">None possible</td></tr>
<tr><td>Action prompt:</td><td colspan="5">Not applicable</td></tr>
<tr><td>Effect:</td><td colspan="5">A HUMS could not have affected the outcome of this occurrence.</td></tr>
<tr><td colspan="6">Application of non-HUMS prevention and mitigation technologies</td></tr>
<tr><td rowspan="3">Technologies applicable</td><td>DC</td><td>IF</td><td>SBU</td><td>FBW</td><td>SLP</td></tr>
<tr><td>HYD</td><td>SRU</td><td>BUCS</td><td>AFCS</td><td>ECS</td></tr>
<tr><td>DF</td><td>TTDD</td><td>VCF</td><td>CNR</td><td>RSDS</td></tr>
<tr><td>Comment</td><td colspan="5">A drag chute or inflatable fin would have helped reduce yaw rate and reduce aircraft damage. The other technologies would have provided no benefits during this occurrence.</td></tr>
</table>

Appendix B Tail rotor failures – advice and considerations

1 Authorship and purpose

This appendix was written by Steve O'Collard of CHC Scotia Ltd (part of CHC Helicopter Corporation). Its aim is to provide a professional pilot's eye view of the AFS trials reported on in Section 6, and includes generic TRF advice and considerations to provide awareness and provoke debate within the piloting community.

2 Introduction

I was one of the pilots involved in a tail rotor failure (TRF) simulation trial at QinetiQ Bedford but I've been disidentified, so I can't tell which one. I originally wrote the substance of this appendix because I was surprised by what we discovered. I was also aware that the problems of tail rotor malfunctions were not well understood by a lot of pilots. I wanted to produce an outline of the trials, a summary of the results and a guide to what these results logically led to in terms of recommendations for pilot actions – in effect an emergency checklist. My intention is not for you to ignore Flight Manual advice but merely to give you more information, to enable you to think more carefully about your particular aircraft type and the implications of a TR malfunction.

The trial followed on from earlier MOD work which had involved wind tunnel, simulation and flight trials and which was triggered by the high rate of TRF accidents in UK military helicopters. The aim of the military work was to provide validated (as opposed to "best guess") advice to aircrew for the Lynx, and resulted in substantial changes to the recommended emergency procedures. The CAA then became involved and the scope of the trial was widened to encompass both military and civil helicopters. The scope included a review of historical accident data, an analysis of the potential beneficial effects of HUMS, a general review of flight manual advice to aircrew on TRFs (which is on occasions poor, misleading or virtually absent) and a study of the current civil and military airworthiness requirements (which are often too general to be of much use. Data from routine base checks in simulators were collected and analysed in the mid 1990s [23]. Intervention time data from this work was used to define some parameters for the trials we flew in the AFS at QinetiQ Bedford in April and June 1999. The purpose of these trials was to examine flight characteristics of the model in TRFs and to then investigate whether things could be improved by modifying the aircraft.

3 Simulator trial

The AFS is the largest simulator in Europe; it basically consists of a cockpit module mounted in a lift, with 10 metres of heave and 4 metres of sway freedom in addition to the normal pitch roll and yaw rotations. The visuals are fairly basic, although adequate for the task, and the cockpit itself has only basic instruments. Flying controls and the seat were from a Lynx and the relative positions were sized as a Lynx. The collective was wired with a NR beep and a "push OFF push ON" engine kill switch. The simulation model on which the majority of work was done is a very accurate model of a Lynx with aerodynamic characteristics derived from scale model wind tunnel tests as well as flight data. Some work was done on a "soft" main rotor, which was achieved by reducing the blade stiffness term to produce characteristics of approximately 4% equivalent hinge offset (i.e. broadly the handling and response characteristics of a Super Puma or S76). This was to provide data to underwrite some degree of read-across of the results from the Lynx-specific model to a wider variety of helicopter types.

Failures were categorised into 2 types: drive (TRDF) and control (TRCF). The TRCF category was further subdivided into high power, low power and mid power TRCF. High power was taken to mean failure to a setting equivalent to high total power, i.e. producing high anti-torque thrust. Low power failure was the opposite and could therefore include producing some degree of pro-torque thrust, depending on the helicopter type. Mid power was taken to imply a control freeze at a setting close to the normal mid position of the yaw pedals. All were assessed from a nominal starting point of 3000 feet at 80 and 140 knots and from the hover; some high power TRCFs were repeated from a 50 feet hover. Most failures were left for 2 seconds from initiation, timed by a horn, before recovery action was started. Towards the end of the trial, intervention times of 1 and 4 seconds were also evaluated for certain failures. The TRDF was simulated by causing the TR thrust and torque terms to reduce to zero over a period of 1 second. TRCFs were simulated by setting the TR angle to move to the failure condition with a 4 second run time. The Lynx has a TR pitch angle range of +26° to –9° in flight due to the collective to yaw interlink. Previous flight trials with the interlink removed had successfully explored the range of +13° (full power pedal without the interlink) to –5° (about 12% and 61% pedal respectively) but could not expand the envelope further due to airframe sideslip limits. This simulator trial evaluated the full Lynx range but we realised very quickly (after I seriously crashed the motion) that full power pedal was not recoverable. We therefore limited the trial to the range of control from which recovery and a landing under some degree of control appeared just possible, which was from +21° to -4°. I have included a diagrammatic representation of TR thrust versus pedal position for the Lynx in Figure B-1 to help explain the problem. For French helicopters, the direction of rotation of the rotor would of course be reversed.

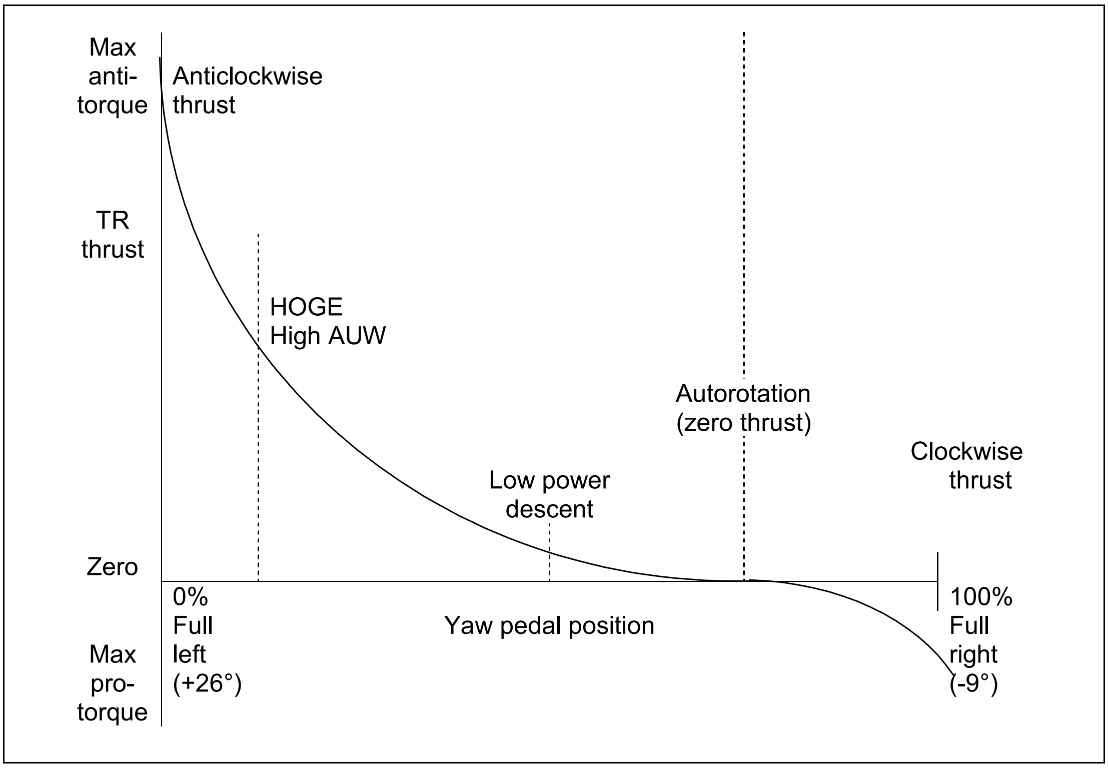

Figure B-1 TR thrust variation with pedal position

Overall, some 50 hours were spent in the simulator over the trial period. Failures were divided into 3 phases: transient, manoeuvre and landing. The transient phase included the initial failure, transient aircraft reaction and pilot recovery action until such point as the aircraft was under control (if ever), which was when the pitch, roll and yaw rates were zero. The manoeuvre phase covered just that: an assessment of the ease or otherwise with which the aircraft could be turned and manoeuvred to a desired landing area. The landing phase comprised the final 200 feet or so of the descent. Each test point was flown by at least 2 pilots and all points were rated according to a comprehensive scale considering such factors as the ability to perform the task (easy, difficult, impossible), workload, aircraft limitations, simulation cues and the likelihood or otherwise of successful recovery. Landing ratings were based on a subjective assessment and were based on the proviso that the landing surface was ideal; in reality this will not be the case. You should be aware that the chances of successful recovery from a full deflection TRCF in the majority of helicopters are probably very low indeed. This will be discussed in more detail later in this paper.

4 TRDFs

The symptoms of a TRDF are an increasing yaw rate away from the power pedal (i.e. to the right in the S76/S61/BO105, to the left in French helicopters). The yaw rate and acceleration are dependent on three factors: power applied at the time of failure, speed at the time of failure, and directional stiffness or residual stability of the helicopter airframe itself (i.e. without the TR). They will therefore be greater the more power is applied and the less directionally stiff the helicopter is. Directional stiffness will be due to a combination of factors, including the size and camber of the vertical fin and also size and setting angle of any horizontal stabiliser end plates. The prime aim of such aerodynamic characteristics is to allow the TR to be offloaded in forward flight. The effect of airspeed was interesting. For the Lynx model, at around V_y (best rate of climb speed), there was little cross-coupling and the helicopter tended to rotate in a relatively horizontal attitude. At high speed, due to the high power applied, the yaw rate was rapid, reaching over 60° per second. Sideslip angle tended to reach 60° within 2 seconds (i.e. normally before recovery action was initiated). As the helicopter sideslip angle increased, the rotor disc flapped back in the roll axis causing a severe roll to the right, although with little pitch attitude change, provided the stabilisation was engaged. The rotor disc was exposed to very high inflow and this induced a rapid increase in the rotor speed towards, or in most cases above, the transient power-off limit, exacerbated at about this stage (2 seconds after the failure) by the recovery action of lowering the collective! The increased rotor speed caused a significant increase in thrust and hence ‘g’ loading on the rotor, up to over 2g. The other noteworthy effect of this motion and g increase was a rapid reduction in airspeed. None of the pilots involved opposed the rolling motion with significant amounts of lateral cyclic, probably due to disorientation and the fact that we were just trying to hang on. It is likely that the severity of the rotor speed increase would have been significantly reduced had the roll been more opposed. Maximum attitude changes at recovery could be of the order of 150° in yaw and over 90° in roll (we did see nearly 180° on one occasion). When a ‘soft rotor’ was modelled (to simulate an S76 type helicopter) it was noteworthy that pitch cross coupling was also significant, even with a stabilised aircraft, and nose down values of at least 50° were seen as well as the yaw and roll excursions.

Recovery action of lowering the collective and shutting down the engines was effective and the aircraft could be stabilised in side-slipping forward flight at around V_y with the loss of around 1000 feet if the failure occurred in the cruise. For failures in the hover out of ground effect, the cross coupling was not anywhere near as significant and it was just a case of taking recovery action, holding about 15° to 20° nose down and waiting for the rotation to stop and airspeed to increase towards V_y. This would normally involve at least 1500 feet of height loss. Ideal hover heights therefore would seem to be either below 15 feet or above 2000 feet. For intermediate hover heights, the engines should probably not be shut down until the yaw rotation has ceased. If insufficient height is available for this, at least the engine power may be used to cushion the impact. For example, to shut down the engines after a tail TRDF in the hover at 200 feet will further reduce the chances of survival to negligible. It is also important to emphasise here that the engine shutdown was achieved with the kill switch, as there was no simulation of engine throttle levers. In the real event, use of throttles or fire handles to shut down engines would require a fair degree of crew co-ordination and rather more time than in this simulation, thereby delaying the effect of recovery action. Some work was done with increased yaw stiffness (by increasing the lift curve slope of the fin, simulating a larger fin) and this was effective in reducing the yaw rates and the height loss for recovery in forward flight. It was in some cases possible to fly the aircraft with some power applied (the “power speed combination”) and therefore reduce the rate of descent. A good rule of thumb appeared to be to lower the collective at a rate proportional to the yaw rate. This will be significant for helicopters with high residual yaw stiffness in the airframe, such as the Dauphin, Gazelle and Squirrel (the latter has been flown successfully in level flight with the TR stopped). This “rule” will however ensure that you react according to the characteristics of the helicopter you are flying. It is important to remember, however, that in helicopters with high yaw stiffness, although the TRDF itself may not provoke any significant yaw reaction, a subsequent reduction of collective pitch will induce a yaw in the opposite direction, as if the TR pitch had failed to a high anti-torque setting. For the low yaw stiffness case, as demonstrated by the basic Lynx model, it was noticeable that if the engines were not shut down and an attempt was made to find a power speed combination once established in autorotation, the aircraft would depart again in yaw and there might not be sufficient height to recover. If the initial yaw rate is sufficient to cause the pilot to lower the collective rapidly, therefore, the engines should be shut down as soon as possible.

Manoeuvring the aircraft in autorotation at around V_y was possible but not always easy, depending on the rate of descent and inherent sideslip due to the cambered fin. The Lynx (among many other helicopters) has a cambered fin to offload the TR in forward flight. In autorotation, therefore, there is still a force equivalent to some power pedal applied, which results in sideslip to the right (in this case, i.e. away from the power pedal side). It was significantly easier to turn away from the direction of sideslip, i.e. away from the yaw due to the failure.

Conventional advice is for a run on landing at the highest speed compatible with the terrain. However, if there is inherent sideslip, this will increase with forward speed and it would appear that in this case, at least, it is better to reduce speed in the flare as much as possible to minimise the possibility of rollover on landing. Once again, the stiffer the helicopter is directionally, the easier the landing should be.

5 TRCFs at high power settings

The symptoms of a high power TRCF are a slow yaw rate towards the power pedal (i.e. to the left in the S76/S61/BO105, to the right in French helicopters). The rate will depend on the pitch angle to which the rotor has failed. If the pitch has failed at a high power setting, rather than run to full travel, the failure may well not be apparent until power changes are made. The pitch angle at which the TR has failed could be estimated by flying at V_y and attempting to centre the slip ball with collective. If the aircraft was still sideslipping right (i.e. away from power pedal, away from the failure) at maximum torque, then the pitch angle was high and the TR was producing too much thrust; recovery would therefore be difficult. The amount of available travel will also depend on the design requirements of the helicopter. For example, military helicopters tend to have powerful TRs and small fins to give good out of wind hover performance, at the expense of reduced directional stability. The majority of this discussion concerns runaways to a recoverable pitch setting. Failures in forward flight were countered by opposing yaw with cyclic (i.e. cyclic in the direction of flight) and if possible increasing power to compensate for the increased anti-torque effect. As previously mentioned, full power pedal failures in the Lynx model in the hover were not recoverable. At an intermediate setting, the aircraft could be flown away from the hover by a gentle climb, accepting the yaw rate, which in any case reduced as power was applied, and then dived to achieve forward speed. The heavier the aircraft, the better, because more power is required anyway and the TR is more likely to be operating close to its maximum thrust.

The aircraft would stabilise in forward flight on a steady heading, with sideslip away from the power pedal and probably a rate of descent which might well be significant. Speed must not be reduced below V_y or yaw control may be lost again and there may not be sufficient height available to recover. Sideslip reduced as airspeed reduced, because the reduction in inflow reduces TR thrust. Manoeuvring in either direction was possible, although significantly easier in the direction of sideslip; variation of collective position could be used to help the aircraft round the turn. It was noticeable that turning in the direction of failure (i.e. towards the power pedal) made the airspeed reduce rapidly. A significant nose down attitude (with associated rate of descent penalty) was required to maintain airspeed at or above V_y.

The landing strategy required an approach track into wind (i.e. wind from the direction of sideslip); the stronger the wind, the better. The basic technique was to drift the aircraft into slow sideways flight, perhaps with a gentle climb rate, to use the maximum power possible. If the technique of a slow approach on the back of the drag curve were attempted, yaw control would be lost as power was reduced. Once approaching the ground (or in the low hover if this is where the failure occurred), it would soon become apparent whether the situation was recoverable without additional action. If the failure were at a sufficiently “low” setting, it would be possible to fly the nose to the right of the flight path with cyclic, then lower the collective gently to align the nose with the track and run on. If more control over the yaw rate were necessary, the answer was to reduce the rotor speed (either by beep or power lever/throttle reduction, depending on helicopter type). As rotor speed is reduced, TR thrust will reduce, but torque will rise (to maintain height/velocity) so total power will remain constant. This will have the same effect as reducing the TR angle and therefore the severity of the failure. An extension of this solution would be to shut down one engine and top the other to basically over-pitch the helicopter. If the failure pitch angle was large, the outcome was normally high-speed sideways flight close to the ground, in the direction of sideslip. Any attempt to carry out a sideways quickstop and dump the collective, as a means of minimising sideways velocity and putting the aircraft on the ground, resulted in a yaw breakaway in the direction of failure (to the left in this case) followed by rapid yaw acceleration and complete loss of the plot. Faced with this situation in reality, I would seriously consider a power on ditching at a reasonable speed, putting the tail in the water first to straighten the aircraft up. This might of course have the added advantage of shearing the TR drive and aligning the aircraft with the track immediately before your feet get wet. If the failure occurs in a low hover, the best solution is to land immediately, before the rotation rate increases too much.

6 TRCFs at low power settings

The symptoms of a low power TRCF are a slow yaw rate away from power pedal (i.e. to the right in the S76/S61/BO105, to the left in French helicopters). The rate will depend on the pitch angle to which the rotor has failed. If the pitch has failed at an intermediate power setting, rather than run to full travel, the failure may well not be apparent until power changes are made. The amount of available travel will also depend on the design requirements of the helicopter, as for the high power case. We established that the minimum recoverable value of pitch angle in the simulator was –4°, as opposed to full travel in the Lynx, which is –9°. Recovery action in forward flight was to lower the collective until the yaw rate stopped; the aircraft would then stabilise, with sideslip towards the power pedal and with a significant rate of descent. From the hover, the effects were similar to but not as violent as a TRDF.

The aircraft could again be manoeuvred in the failed condition, although the same conditions applied as for the high power failure case. Collective could be used to help the turn; it was significantly easier to turn left (i.e. in the direction of sideslip); and turns in the direction of failure caused a significant reduction in airspeed. As with the high power failures, the pitch angle at which the TR has failed could be estimated by flying at V_y and attempting to centre the slip ball with collective. If the aircraft was still side-slipping left (i.e. towards the power pedal, away from the failure) at zero torque, then the pitch angle was negative and the TR was producing negative (i.e. too much) thrust.

Landings in this condition were not as simple as would perhaps seem. If the failure were at a sufficiently "high" setting, i.e. somewhere below the neutral position but not at full low pitch, it would be possible to fly the nose to the left of the flight path, then raise the collective gently to align the nose with the track and run on. However, at extreme pitch settings, even if the engines were shut down, the TR was still effectively producing too much pro-torque thrust and therefore the aircraft would still sideslip to the left. As rotor speed decayed in the flare of the engine off landing, TR thrust would reduce and therefore the sideslip would reduce. However, at high failure angles (i.e. negative thrust), the sideslip would still not reduce enough to avert a probable rollover on landing. Rotor speed reduction would be beneficial in the same way as for high power failures in this case. If the TR is still providing an amount of positive thrust (but less than required for the condition) then increasing rotor speed will be beneficial (increased thrust at reduced torque). A technique which did work (but which required some co-ordination and practice) was to keep the engines running whilst manoeuvring and fly whatever profile was necessary to make the selected landing area. The final stage of the approach was flown in or close to autorotation, tracking along the desired landing path. At about the point where the aircraft pitch attitude was reduced prior to touchdown (but not before), the engines were shut down. The resultant yaw to the left aligned the aircraft with the ground track and it ran on straight. It is important to remember at this stage, however, that if the failure is due to a cable break forward of a collective to yaw interlink, lowering the collective rapidly at this stage will cause the aircraft to yaw right (i.e. in the direction of failure, away from the power pedal). Collective pitch should be maintained until rotor speed (and therefore TR thrust) has decayed somewhat.

7 Mitigating technologies

The effects of some mitigating technologies were explored. Increasing the authority of the autostabilisation was helpful in reducing the severity of the transients when the failure occurred, in particular in the roll axis. This had the added benefit of effectively reducing the subsequent g and rotor speed excursions to within design limits. However, this would have penalties in certification due to the greater runaway stroke. A pilot selectable drag chute and an inflatable fin were modelled. They proved effective in controlling the yaw rates on failures in forward flight once the initial failure had occurred and in easing the landing task. However, the drag penalty associated with a chute and implications for longitudinal centre of gravity might make this an impractical solution, even if the certification safety issues (inadvertent deployment?) could be overcome. Furthermore, because the drag chute or fin could of necessity not be deployed until a failure had occurred, they were of no use in controlling the initial transients, which is where the peak stresses occur. For the TRDF case, however, the only modification which would reduce (or nullify) the initial yaw transient (i.e. the initial cause of all the problems) was a fin which offloaded the TR in forward flight. This could mean perhaps a cambered fin, angled horizontal stabiliser end plates or a fenestron (or some combination). The assessed fin had an effective 50% increase in area. However, such systems bring further problems due to asymmetrical handling, because of the roll due to the extra yawing moment from the fin. This may be significant in a low power descent or autorotation, where the tail assembly is providing too much anti-torque thrust and asymmetric roll control power will be required to overcome the extra rolling moment. For TRCFs, rotor speed variation was potentially very effective in controlling yaw, as discussed above.

Finally, simulation of a SBU was by far the most effective for all TRCFs. This is designed to drive the TR to a neutral pitch setting in the event of a failure, such that straight and level flight is possible without sideslip at a mid power setting and a straight running landing can be made at speeds of about 40 knots. A SBU is fitted to the Lynx and EH-101. The negative force gradient spring in the S61 and the compensating spring in the 365N have a similar effect. Note, however, that this type of installation normally requires simplex hydraulic control of the TR, such that the hydraulics can be deselected to allow the SBU to operate. (It cannot therefore work in the 365N2, which has duplex hydraulics to the servo). It will also only work if it has duplex control inputs and can therefore sense failure of one of them; hardover of a "push-pull" rod, due perhaps to mechanical failure, will merely be seen as an acceptable control demand. The Super Puma has a spring rod in the linkage just upstream of the tail servo which is designed to drive the pitch to a mean setting in the event of a cable failure, as it also has duplex hydraulic power to the servo. Preponderance weights as fitted to the BO105 have a similar role. The ideal position for such a device is as close as possible to the actual pitch change links, which is the only way to compensate for all possible upstream failures, including those of the bearings which support the pitch change mechanism through the TR gearbox.

8 Training and simulation

It is apparent from the results of this trial that training for TRFs is important. For this training to be effective, a number of requirements must be in place. The first of these must be that the guidance given in the Flight Manual must be comprehensive, unambiguous, realistic and validated to the highest possible level. The study undertaken for this trial showed that a significant proportion of current Flight Manual advice does not meet these criteria, at least in part. Training for TRFs is not really possible in the aircraft, with the exception of some "jammed pedal" procedures, and it is not normally practical to build simulators for smaller helicopters, so this Flight Manual advice is really the only source of advice for such aircraft. Where simulators exist, they should of course be used as much as possible. However, they will be of little practical use if the model on which the simulation is based is incomplete or incorrect. Pilots will be given a false impression of the handling characteristics of their helicopter, normally in the wrong sense (i.e. it will be worse in reality). For example, a TRDF in one commercial simulator at 70 knots produced an apparently realistic response, yet the same failure at 110 knots produced no reaction until the collective was lowered below 60% torque. It is arguable whether such simulation is actually worse than no simulation at all.

9 Conclusions and recommendations

I have combined the results and my thoughts on the trials with other available advice in various publications to provide what I believe to be reasonable and concise actions and considerations. The philosophy is necessarily general and cannot depict the characteristics of individual helicopter types. It also assumes that you have carried out any procedures specific to your type, such as switching off the Auxiliary Hydraulics in the S61 to bypass the servo and allow the TR to go to flat pitch. It should be noted, however, that the symptoms may not be immediately apparent. It is also clear that rapidly identifying the failure and applying the appropriate corrective action is not always straightforward. The tasks would be made easier if helicopters had sufficient inherent yaw stiffness to contain the transient worst case response within at least structural limits. The design should ensure a fail-safe pitch setting in the event of any TRCF; and it would be ideal if realistic simulation facilities were available.

Please remember, however, that the aims of this section have been to discuss the failures in some detail, to generate interest and to provoke thought, not to replace the appropriate Flight Manual procedure for your helicopter type. I hope I have achieved these aims.