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CAA PAPER 95009

ENHANCED WARNING AND INTERVENTION STRATEGIES FOR THE PROTECTION OF ROTOR SPEED FOLLOWING POWER FAILURE

CIVIL AVIATION AUTHORITY LONDON PRICE £24.00

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PREPARED BY WESTLAND HELICOPTERS LIMITED,
YEOVIL, SOMERSET (REPORT NO RP937 AT/AS4/1272)
AND PUBLISHED BY
CIVIL AVIATION AUTHORITY LONDON OCTOBER 1995

ISBN 0 86039 637 1

Printed and distributed by Civil Aviation Authority, Greville House, 37 Gratton Road, Cheltenham, England

Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority, the UK Department of Transport, and the UK Health and Safety Executive. The work was instigated at Westland Helicopters' Advanced Engineering Department in response to Recommendation 4.4 of AAIB Aircraft Accident Report 4/83, (accident to Westland Wessex 60 G-ASWI 12 miles ENE of Bacton, Norfolk on 13 August 1981), Recommendation 4.2 of AAIB Aircraft Accident Report 7/87, (accident to Twin Squirrel AS355 G-BKIH at Swalcliffe, near Banbury, Oxfordshire on 8 April 1986), and the findings of the Helicopter Human Factors Working Group reported in CAA Paper 87007 (recommendation 4.1.17). The Helicopter Human Factors Working Group was formed in response to Recommendation 1 of the Report of the Helicopter Airworthiness Review Panel (CAP 491). This paper contains the full details of the research carried out; a summary of the work was presented in Paper No. 43, entitled 'The Protection of Rotor Speed Following Power Failure', at the 20th European Rotorcraft Forum, held 4–7 October, 1994 in Amsterdam.

The CAA concurs with the conclusions of this work. At the time of publication, the JAR 27/29 and FAR 27/29 intervention time criteria are under review by the FAR/JAR Rotorcraft Performance and Handling Qualities Harmonisation Working Group. The results of this research have been presented to the Group, and are contributing to the debate on proposed amendments to the requirements. The need for further research in this area, such as that detailed in the recommendations of this paper, will be assessed once the above-mentioned review of the related JAR and FAR material has been concluded.

Safety Regulation Group

25 August 1995

Summary

Air Accident Investigation Branch (AAIB) reports into accidents that have occurred to civil helicopters operating in the UK, have highlighted the failure to control rotor rpm following power failure as a contributory factor in numerous accidents, some of which have resulted in loss of life.

The CAA's Mandatory Occurrence Report (MOR) database has been interrogated during this study to ascertain the historical significance of rotor speed control problems on the accident record of civil helicopters registered in the UK. From this study, it has been judged that had a requirement been in force to fit an enhanced rotor speed protection system since 1976, a significant reduction (82%) in the number of reportable accidents where rotor speed excursions have been a contributory factor may have been achieved. This includes the potential to have prevented, or at least to have reduced the severity of 9 fatal accidents, that resulted in the loss of 29 lives.

While it is acknowledged that helicopter systems, and in particular the engine, have improved in reliability through the years, the design of modern helicopters can make the consequences of any such failure far more severe. Commercial considerations and aircraft performance criteria have tended to influence modern design trends towards low inertia rotor systems which compound the power failure problem by increasing the rotor speed decay rate. This has resulted in a reduction in the time available to the pilot to recover from such a failure.

The unforeseen loss of engine power in any air vehicle has potentially severe consequences. The helicopter, however, has some distinct advantages over fixed wing aircraft, due to its ability to autorotate. Following total power loss, autorotation is possible from virtually anywhere within the flight envelope, provided that the aircraft's height is sufficient and that the pilot acts in a timely manner. The problem which faces the helicopter pilot is that, in the absence of immediate corrective action, power failure may lead to a rapid loss of rotor rpm and that, unless the loss is constrained, safe entry into autorotation will not be achieved. Once autorotation is achieved, the pilot must still maintain control of the rotor speed throughout the subsequent descent and landing. This can result in a very high workload being placed on the pilot, who as well as performing a multitude of other tasks, must continually monitor the rotor speed.

Any increase in available intervention time, achieved through a fundamental change in rotor inertia, could only be realised at the expense of restricting the performance and operational use of the vehicle. This would be commercially unacceptable to operators. The alternative approach is to reduce pilots' actual intervention time by providing improved cues and warnings, or to fit automatic systems which would detect low rotor speed and automatically take the necessary corrective action.

This study was initiated to investigate the extent to which actual intervention time could be reduced using enhancements to current warning systems or by the introduction of automatic systems. In consultation with helicopter pilots and operators, and from the experience of Westland Helicopters Ltd and the UK CAA, a number of possible solutions were postulated, including: enhanced visual systems, various auditory warnings, tactile cues and automatic intervention systems capable of taking appropriate corrective action. All of these strategies have undergone an assessment in this study, both analytically in off-line studies (where applicable), and in a piloted simulation trial.

The most promising systems to emerge from this study are summarized below.

1 **The phase advance filter** – Offers the potential to minimise the delay time between the failure occurring and the pilot being warned of the failure. Typical reductions were found to be between 0·5–1·4 seconds depending on the flight condition and the rotor's power requirement at the time of failure.

2 **Modulated tone** – Believed to offer the best short term method of improving rotor speed warnings, particularly for the control of rotor speed during autorotative descent.

3 **Automatic collective reduction** – Has the potential for a significant improvement in flight safety, although integrity issues would undoubtedly need to be resolved. Inclusion in existing helicopters may also be found to be impractical/uneconomic as may applications to smaller, less sophisticated new types.

4 **Automatic flare system** – This system offers a limited rotor speed protection capability. However, by operating within the limits of existing ASE equipment, integrity issues may be easier to resolve, and the cost of the system reduced compared to the automatic collective reduction system.

Contents

1 INTRODUCTION

This report contains a complete record of all the work carried out by the Advanced Engineering Department at Westland Helicopters Limited (WHL), on behalf of the UK Civil Aviation Authority (CAA) under contract 7D/S/1032.

The contract was initiated primarily as a result of the recommendations made by the Air Accidents Investigation Branch (AAIB) following two accidents, which are summarised below.

(a) The accident that occurred to Wessex G-ASWI off Bacton in 1981. Autorotation was entered but not sustained, killing all 13 people on board (Reference 1).

(b) The accident to an AS355 Twin Squirrel, near Banbury in 1986, killing all 6 people on board. This was thought to be caused by slush ingestion that resulted in loss of power, and the subsequent failure to enter autorotation due to the high level of rotor speed decay (Reference 2).

A number of recommendations were contained in the AAIB reports including a need to review existing warning devices fitted to helicopters and the operational procedures that are adopted in this type of emergency situation. In addition, it was recommended that an automatic mechanism to reduce collective pitch following power failure should be investigated.

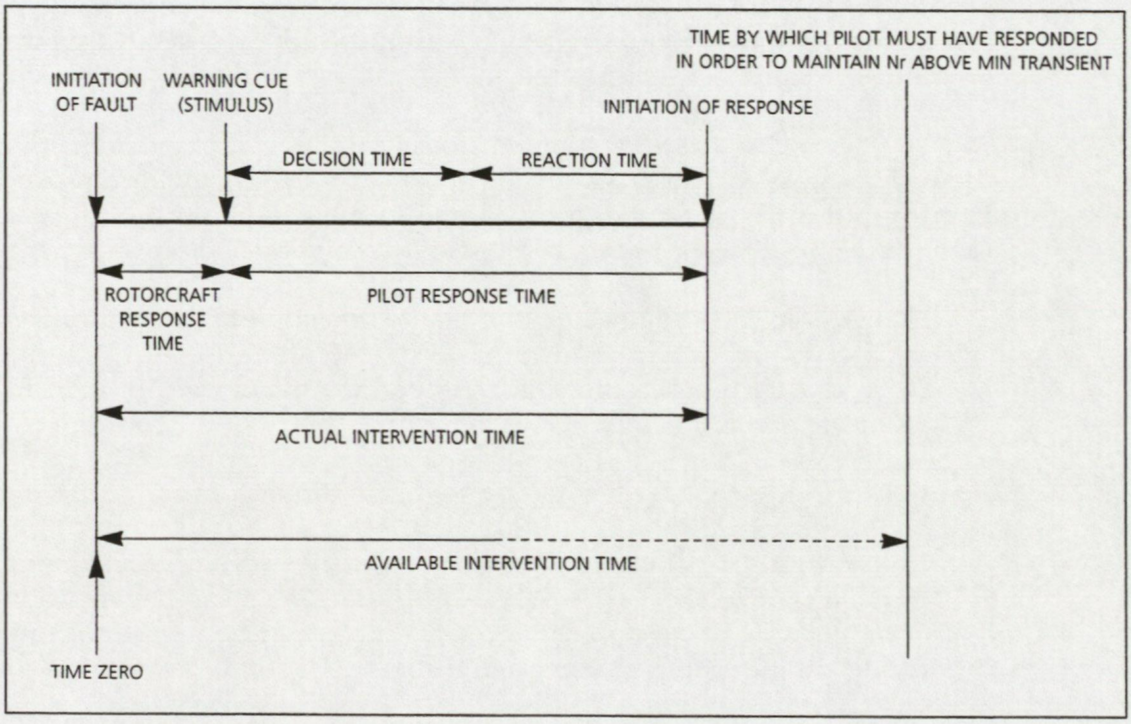
To take up some of these recommendations, the CAA contracted WHL to investigate the technologies available, within the short term, which could improve the short comings identified, and a work programme was initiated. The brochure (Reference 3) outlined a study consisting of the following objectives:

- to review accident statistics and to define the nature and extent of the problem,
- to review current warnings and procedures employed for civil helicopters following partial and total power failures,
- to assess the scope for providing additional warnings,
- to use WHL's experience of advanced control techniques, including Carefree Handling (CFH) (Reference 4) and Integrated Flight and Engine Control (IFEC) (Reference 5), to develop enhanced warning strategies, including: audio, visual and tactile cues (stick shakers and pushers),
- to use the Advanced Engineering Department's fixed based simulator facility to assess the performance of the enhanced strategies in a piloted simulation trial.

2 BACKGROUND

Loss of engine power in any air vehicle has potentially severe consequences. The helicopter, however, has some distinct advantages over fixed wing aircraft, due to its ability to autorotate. Following total power loss, autorotation is possible from virtually anywhere within the flight envelope[1], provided that the aircraft's height is sufficient and that the pilot acts in a timely manner. Having achieved autorotative flight, the landing can then be performed in a very small area, hopefully giving the pilot plenty of scope to select an appropriate landing site and make a successful engine-off landing. Entry into autorotation, however, is not automatic and failure to achieve autorotation, following total power failure, has resulted in many helicopter accidents.

The problem that faces the helicopter pilot is that, in the absence of immediate corrective action, engine failure may lead to a rapid loss of rotor rpm and that, unless the loss is constrained, safe entry into autorotation will not be achieved. Actual intervention time and available intervention time (see table below and Appendix 1 for definitions), can therefore be crucial to the successful recovery following power loss.



Actual intervention time can be thought of as comprising two elements, rotorcraft response time and pilot response time. Rotorcraft response time represents the time taken between the failure occurring and the pilot being alerted to it by a suitable cue. This cue may take the form of: an external noise cue, an adequate tactile, audio or visual warning, or may be perceived by the pilot as a motion of the vehicle. This element should not be underestimated, however, as on some helicopters and in some operating conditions, an engine may fail without distinguishable noise or motion cues.

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1 Entry into autorotation can be limited in the 'avoid areas' of the height-velocity diagram due to the combination of height and speed. These avoid areas are well defined in flight manuals and pilots are advised not to operate in them.

Pilot response time can be subdivided into the following two elements.

(a) *Decision Time*

This represents the time taken by the pilot to recognise and interpret cues and warnings to identify the problem, as well as the time required to select the appropriate corrective action. Decision time will be dependent on the attentiveness of the pilot, the perceived strength of the cue in alerting the pilot to the problem, and the training and experience of the pilot. In complex helicopters, decision time may be adversely affected by the non-specific nature of available cues, requiring the pilot to perform diagnostic procedures to home-in on the failure condition.

The action to be taken by the pilot following a failure is also not unique, but may require the pilot to make a judgment as to the most appropriate control inputs to make, based on his speed and height. This may require either the lowering or raising of the collective lever and/or pushing/pulling of the cyclic control.

(b) *Reaction Time*

Reaction time is defined as the time taken by the pilot to react to his decision and commence recovery action. Reaction time will be dependent on whether the pilot is flying 'hands-on' or 'hands-off'.

The objective of regulators must be to ensure that actual intervention time is never greater than the available intervention time. This can be achieved through either of two ways, reducing actual intervention time or increasing available intervention time.

Increased available intervention time, achieved through fundamental design changes, could only be realised at the expense of restricting the performance and operational use of the vehicle. The rate of rotor rpm decay following total power loss is dependent on the rotor inertia and the in-plane drag forces on the blades, i.e. the rotor torque requirement. It would therefore be necessary to redesign the rotor to have a high inertia and/or to restrict the torque requirement of the main rotor by limiting the flight envelope and/or all-up-mass (AUM). All of these measures would be commercially unacceptable. Some novel systems such as emergency tip jets or some form of stored energy device, such as a flywheel, may offer longer term solutions, but are beyond the scope of this study. There is some scope to increase the available intervention time however, through the use of automatic intervention techniques.

Figure 1 shows the strategy developed during the IFEC programme, undertaken by WHL on behalf of the UK MoD, for an automatic system that would take the initial recovery action following total power failure. The pilot is assumed to regain control following this initial automatic action and to take the subsequent action to complete the descent and landing procedures.

Considering actual intervention time, the reaction time element will generally be fixed for a given pilot involvement level. Factors that may have an influence on reaction time are the cockpit ergonomics and the physiological condition of the pilot (age, fitness, health). The effects of these factors are outside the terms of reference for this study, and are therefore not addressed here. The remaining elements, the rotorcraft response time and the decision time, are seen as offering scope for improvement through improved state monitoring and the use of enhanced warning techniques.

As well as the initial action required by the pilot to control rotor speed following power failure, it is also important that the pilot maintains the rotor speed within acceptable limits throughout any subsequent autorotative descent. Failure to constrain rotor speed during autorotative descent may have been the cause of some accidents (e.g. Ref 1), and is therefore an aspect that needs to be considered here.

To summarise, the areas identified which offer some scope for improvement are as follows:

- reduced rotorcraft response time, through improved state monitoring,
- reduced decision time, through the use of improved warnings provided to the pilot,
- increased available intervention time, through the use of intervention techniques designed to automatically detect engine failure/rotor speed loss and take appropriate action,
- improved pilot awareness of rotor speed during autorotative flight, through the adoption of an appropriate warning strategy.

3 EXTENT OF THE PROBLEM

Although the two accident reports cited in the introduction initiated this study, a review of the CAA's Mandatory Occurrence Report (MOR) database highlighted the fact that the problem was more widespread than had been thought. With the help of the CAA, a more extensive interrogation of the database was performed, (Reference 6), using a number of key phrases[2], and the resulting statistics classified in terms of the following:

(i) single and twin-engine helicopters,

(ii) the phase of flight in which the accident occurred,

(iii) whether the accident was fatal or not.

In addition, a subjective interpretation of the accident reports has been made with the assistance of a CAA test pilot. This was done to determine the effect that the rotor speed had on the accident and whether the use of some form of rotor speed protection system would have helped the pilot retain control. Each accident is caused by a unique set of circumstances to which individual pilots will react differently. The action taken by a pilot in this high workload scenario can only be estimated from the limited information available in accident documentation. The data has therefore been broadly classified in the following three categories:

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[2] The key phrases used were: 'engine failure/malfunction', 'main rotor rpm' and 'autorotation'. For ease of presentation they are grouped together as 'rotor speed excursions' in this report.

Highly probable	–	It is considered highly probable that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.
Probable	–	It is considered probable that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.
Improbable	–	It is considered improbable (or unlikely) that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Tables 1 and 2 summarise the results of the statistical and subjective analysis undertaken using the MOR database. Data from 1976 (the date at which the database began) up to July 1993 has been incorporated in the tables. Only 'Reportable Accident'[3] data involving 'rotor speed excursions' has been considered in this analysis, as this data represents the most severe of the failure occurrences. Any enhanced rotor speed warning system would therefore be judged on its ability to prevent this type of occurrence. The main conclusions are highlighted below.

1 The total number of UK reportable accidents recorded on the MORS database involving 'rotor speed excursions' is 87, of which 10 were fatal.

2 Of these 87 reportable accidents, 78 (90%) involved single-engine machines, of which 6 were fatal.

3 9 reportable accidents involved twin-engine helicopters, of which 4 were fatal.

4 For single and twin-engine helicopters combined, all of the reportable accidents in the 'Highly Probable' category occurred in cruise flight.

5 For single and twin-engine helicopters combined, the majority of the reportable accidents in the 'Probable' category occurred in low level flight (54/67, 81%).

6 Only 1 reportable accident involved an Nr increase and in this case it is considered that any additional warning or intervention techniques would probably not have helped the pilot retain control.

7 It is considered either 'highly probable' or 'probable' that the fitting of additional warning/intervention systems to aid rotor speed protection would have helped the pilot in 65 reportable accidents (83%) involving single-engine helicopters, and 6 cases (67%) involving twin-engine machines (82% in total).

8 In 9 out of the 10 fatal accidents, it is considered either 'highly probable' or 'probable' that if an additional warning/intervention system designed to protect rotor speed had been fitted, it would have helped the pilot control the aircraft, with the potential saving of 29 lives.

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3 A 'reportable accident' is an occurrence which results in death or serious injury to any person as a direct result of an aircraft's operation, or where the aircraft incurs substantial damage or structural failure. The full definition can be found in the Air Navigation Order, Section 8.

To help put these statistics into perspective, the CAA provided the following information on general civil helicopter operations within the UK.

- Between 1976 and July 1993, there are 420 UK helicopter reportable accidents (all causes) on the MOR database relating to helicopters, of which 50 were fatal accidents (33 single/17 twin).

- The number of helicopters on the UK register (at 1 April 1993) with a valid certificate of airworthiness or permit to fly was 714 (519 single/195 twin).

- An estimate of the flight hours flown by helicopters since 1976 has been gauged as being of the order of 1 million (single) and 2 million (twin).

Analysis of these statistics indicates that reportable accidents where 'rotor speed excursions' have been a contributory factor account for 21% (87/420) of all reportable accidents. Furthermore 20% (10/50) of all fatal accidents can be accounted for in this way.

The reportable accident statistics would indicate that single-engine helicopters are more prone to accidents where 'rotor speed excursions' have been a contributory factor. Mean time between failures that have resulted in a reportable accident, can be estimated as:-

$$\text{Singles} \quad \frac{\text{78 reportable accidents}}{\text{1 million flight hours}} = 7{\cdot}8 \times 10^{-5} \text{ accidents/flight hour}$$

$$\text{Twins} \quad \frac{\text{9 reportable accidents}}{\text{2 million flight hours}} = 4{\cdot}5 \times 10^{-6} \text{ accidents/flight hour}$$

This would imply that the problem in single-engine helicopters is at least an order of magnitude greater than for twin-engine machines. This tends to confirm theoretical predictions of the relative accident rates expected between these two helicopter classes. In single-engine helicopters, engine failure will immediately result in a loss of rotor speed and the pilot is therefore obliged to take immediate corrective action. Furthermore, private pilots, who form the majority of the single-engine class, will in general be less well trained than their commercial counterparts, and may be inexperienced at dealing with the emergency situation. In the event of a single engine failure on a twin-engine machine, the operative engine will automatically attempt to maintain rotor speed and a contingency rating can be invoked to maintain the required power level to sustain flight in all but the highest power conditions. The action required of the pilot may therefore no longer be urgent. A failure resulting in a loss of engine power in a single-engine machine, (either directly or as a consequence of a first failure, such as a tail rotor or transmission failure), may be further exacerbated by the type of terrain over which the aircraft is flying at the time, as the pilot is constrained to land immediately. In the case of multi-engine helicopters, however, the pilot may be able to fly away from an undesirable area so that a more suitable landing site can be selected.

Total power failure on a multi-engine helicopter is very rare. In consultation with pilots, there were very few who had any experience of this type of failure, and in cases that were disclosed, the failures were not simultaneous but successive. Some unjustified complacency was thought to exist, particularly among the less experienced pilots, that this type of failure could not occur. Four common cause failure modes have been established which have the potential to trigger a simultaneous multi-engine failure:

- slush/ice ingestion,
- fuel contamination/starvation,
- damage to the second engine following a catastrophic mechanical failure of the first,
- failure of common transmission components.

Multi-engine helicopters are generally poorer autorotational performers than single engine machines. In the event of a total power failure, or some other failure such as transmission or tail rotor failure, the consequences on the multi-engine machine are potentially that much more severe. This may be one reason why there is a higher fatality rate in twin-engine helicopters; 4/9 (44%) of reportable accidents for twin-engine machines were fatal, as opposed to 6/78 (8%) for single-engine helicopters. Other factors that will have a bearing on these statistics are: training, the attitude of the crew, and the potentially more severe operating conditions to which twin-engined helicopters are typically exposed.

The statistics indicate that 'rotor speed excursions' which have contributed to a reportable accident, are significant in both cruise flight and in low level flight, (30 and 57 respectively). From these values, it has been judged that an enhanced rotor speed protection system would have benefited the pilot in maintaining control in 17 reportable accidents (57%) which occurred in cruise flight and 54 accidents (95%) which occurred in low level flight. While both of these areas of operation are important, and will be considered in this study, it is noteworthy that 8 out of the 10 fatal accidents occurred during cruise flight.

In summary, the following points have been established:

- The database analysis indicates that reportable accidents where 'rotor speed excursions' have been a contributory factor are more prevalent on single-engine machines.
- Accident rates in both cruise flight and at low level are significant and should be addressed in this study.
- 82% of all reportable accidents involving this type of failure could potentially have been prevented, or reduced in severity, if an enhanced rotor speed warning had been fitted.
- 18% (9/50) of all fatal accidents which occurred between 1976 and July 1993 could potentially have been prevented, or reduced in severity, by the use of an enhanced rotor speed protection system, with a potential saving of 29 lives.

Hence the use of a rotor speed protection system to prevent Nr decreasing to unsafe levels is seen as a method of significantly improving the safety level of rotorcraft and reducing the overall level of fatalities sustained in civil helicopter operations.

4 CURRENT WARNINGS AND PROCEDURES

The types of warnings and cues that are currently used by a pilot to detect rotor/engine problems, can be separated into three categories: visual, audio and kinaesthetic. Each of these types of warnings is discussed in the following sections.

4.1 Visual Warnings

For engine failure cases, there will not normally be any external cues visible to the pilot. The normal individual engine instrumentation fit within the cockpit, namely: compressor delivery pressure P3, turbine entry temperature T6, engine torque output, and speed gauges Ng and Nf, would normally indicate if a problem existed, and may distinguish which engine had failed. However, instrument indications may not be immediately noticed by the crew, particularly in daylight conditions when the pilot is flying VFR, nor can they be relied upon to distinguish abnormal conditions sufficiently early to be regarded as an adequate cue. To improve this situation, many helicopters are fitted with a Central Warning Panel (CWP) which highlights faults and categorises them as a function of severity; 'Warning'(red), 'Caution'(amber), and 'Advisory' (green). These may be accompanied by a flashing 'attention getter' in front of both pilots in the case of a severe fault resulting in a warning, such as engine failure, which requires an immediate reaction from the crew. (Some aircraft types may also have caution attention getters and/or accompany the visual cues with an audio tone to further ensure that the pilot is aware that there is a problem).

Table 3 summarises the information that is presented on the CWP, following an engine failure for a range of civil helicopters. It must be remembered that many of these indications are not exclusive to complete engine failure. They can individually appear with the master caution light, if appropriate, to warn of engine and/or rotor problems that do not always lead to engine failure.

4.2 Audio Cues and Warnings

The first indication to the pilot that something may be amiss is often through the sound of a mechanical failure and/or a change in the rotor/transmission/engine noise. These are very powerful cues that immediately get the attention of the crew. However, these external indications are not present on all aircraft types and may not be applicable to all engine failure modes. They cannot therefore be relied on to detect a reduction in rotor speed.

The number of audio warnings generated from on board instrumentation has increased in number and complexity over recent years. In older types there may be none. In modern low technology machines the use of a simple horn to warn of low rotor speed may be provided, while the latest systems for more advanced types comprise a multitude of tones and spoken messages which include warnings as well as cautionary and advisory information. Audio warnings are generally perceived as the most powerful category of warnings, as they are not reliant on the pilot being attentive. Table 3 also includes a comparison of the audio information which is provided on civil helicopter types.

Three types of audio warnings are in general usage: a tone, a spoken message, and one that combines the two, giving a tone followed by a message.

4.2.1 *Tone Warnings*

Different tones, set at different frequencies, are used on many aircraft types to identify particular failure conditions. On less sophisticated helicopters, a single tone, in the form of a low rotor speed horn, may be the only audio tone fitted, yet it is one that is effective in that the pilot is trained to react immediately to this warning by lowering the collective lever fully.

Audio tones are often preferable in dynamic situations, such as when trying to control the rotor speed during autorotative descents. If a low and high rotor speed audio tone is provided, the pilot is able to maintain rotor speed within limits by making small adjustments to the collective position without reference to instrumentation. The pilot is therefore able to perform other tasks such as locating a suitable landing site and issuing a Mayday call.

4.2.2 *Message Warnings*

To obviate the necessity for the pilot to remember what tone warnings mean, devices such as AVAD (Automatic Voice Alerting Device) have been introduced on some helicopter types to provide a spoken warning. Such a device is mandatory for helicopters operating in the North Sea to provide a low height warning. This type of warning, normally in the form of a soft female voice, is designed to inform the pilot of a problem without inciting panic (which tone warnings are prone to do).

The only limitation on message warnings is the capability of the AVAD device, but the main disadvantage of this type of warning is the finite time required to complete the message, making them ineffective in dynamic situations.

4.2.3 *Tone + Message Warnings*

To overcome the inherent disadvantages with tone and message warnings a third type was introduced which combines the advantageous features of both, giving a short tone followed by a spoken message. The type of tone is again unique to a particular failure condition, and can therefore be immediately interpreted by the pilot. The message confirms the type of fault as well as reducing the number of tones required by specifically identifying a particular fault (e.g. 'Fire Engine 1').

4.3 **Kinaesthetic Cues**

This category of cues/warnings is related to the motion felt by the pilot. In trimmed flight the tail rotor supplies the required moment to counter the torque produced by the main rotor drive system, thus preventing the fuselage from rotating. Following an engine failure the torque supplied to the rotor may be reduced, giving rise to an imbalance of moments in the yaw axis. This will cause the helicopter fuselage to turn in the same direction as the main rotor (as distinguishable from a tail rotor failure that will cause the fuselage to yaw in the opposite sense). The severity of the yaw rate will depend on the magnitude of the moment imbalance, i.e. whether a single or multiple engine failure occurs and the power requirement of the rotor.

Again, this type of cue can be useful in diagnosing the problem, but it is dependent on a number of factors, including helicopter type, and must therefore be considered an unreliable cue for engine failure detection. It may also be difficult to distinguish from a yaw axis ASE failure without any corroborative cues.

4.4 Procedures

On detection of a low rotor speed condition, the action required of the pilot will be dependent on height and speed, and may involve primary inputs into both collective and fore/aft cyclic channels. In addition, secondary inputs may be necessary to correct roll and yaw attitude. (In the yaw case, any collective/yaw interlink will now work against the pilot). At low altitude and low speed, entry into autorotation should not be attempted, but the collective lever raised just before the aircraft touches down to cushion the landing. At high altitudes autorotation can be entered, with the best forward speeds being at the minimum power speed, (for minimum rate of descent and therefore maximum flight time), or at a slightly higher speed to give the maximum range in autorotation. To enter autorotation in the hover or low forward speed, a longitudinal cyclic input may be required to dive the aircraft and, at high speed, a cyclic flare may be appropriate in conjunction with lowering the collective lever.

There are areas in the flight envelope within which the crew should avoid operation. These areas represent parts of the envelope where, despite the pilot's actions, some amount of damage may occur following a failure. Figure 1 shows a typical example for a total power failure. The low hover height represents the maximum altitude from which the aircraft would not sustain any damage if the pilot elected to come straight down, maintaining the current collective position and cushioning the landing using the remaining collective available. The high hover height represents the minimum height at which the pilot could successfully make a diving transition into, and recover from, autorotation, without exceeding the landing constraints.

A single engine failure in a multi-engine installation may not require the pilot to take any immediate action, as long as the remaining operative engine is able to compensate for the failed engine and generate sufficient torque to maintain rotor speed. This will be the case in all but the highest power conditions, (hover and low speed flight, high speed flight and climb). In these conditions, it may be necessary to reduce the collective to maintain rotor speed and in the case of a non-FADEC engine, to prevent the good engine from exceeding its contingency limits and risk failure of a second engine. If the helicopter is fitted with a low rotor speed audio warning, this warning is often used in operating procedures to establish the appropriate collective setting for the single engine flyaway case.

4.5 Correlation of Warning Types to Accident History

Correlation of the reportable accident statistics contained in Table 1B with the type of warning system fitted to the helicopter type in question, does not identify any particularly favourable system. The use of a horn to warn of impending low rotor speed has undoubtedly prevented many accidents. However, the accident record indicates that this system may not be the full answer as some accidents, and loss of life, have still occurred which may have been potentially avoidable if further enhancements had been included.

5 TRAINING

Training is fundamental to the safe operation of any vehicle. The exposure of flight crews to potential failure modes on a regular basis will ensure that pilots know hov to recognise and diagnose particular failures and what subsequent corrective acti‹

to take. This will ensure that the pilots' decision time can be kept to a minimum so that potential problems are dealt with in a timely manner and do not escalate in severity to a level affecting flight safety.

Civil pilots flying public transport operations and holding a CPL(H) or ATPL(H) are continually reassessed at regular 6 monthly intervals through 'base checks', which include both VFR and IFR procedures as appropriate. This includes entry into autorotation following the simulated failure of the single engine or the successive simulated failure of engines in the twin engine case, autorotative flight and recovery. Although there is no requirement to carry out power-off landings on recurrent testing, the recovery is to powered flight usually after a flare to either the hover or to a flyaway.

Where a simulator is available, one VFR and one IFR base check are performed in this facility each year. The simulator is perceived by the pilots to be an extremely valuable tool to improve their experience of these high risk situations, and pilots would generally like to spend more time using this facility than they are currently allocated.

Private pilots have a far more relaxed set of rules under which they operate. There is no requirement for private pilots to practise emergency procedures once they have gained their licence, the only constraint being to achieve a given total number of flight hours each year.

Pilots of single-engine helicopters are trained to maintain hold of all flying controls whenever possible throughout the flight, to minimise their reaction time. It is also considered good piloting practice to select potential landing sites while en-route, should it be necessary to perform an emergency autorotative landing. Total engine failures on multi-engine helicopters are very rare, however, and so the need to maintain this piloting strategy is less important and is often not adhered to, except during single engine operations.

6 PAST AND CURRENT WORK PROGRAMMES

Table 3 indicates the diversity in warning strategies adopted by manufacturers. It is also indicative of the amount of work that needs to be done in this area to provide the most effective and ergonomic warning strategy. The standardisation of warning strategy across manufacturers would be a welcome goal and would undoubtedly give benefits to pilots, especially those who fly more than one helicopter type.

In the recent past, a great deal of effort has been expended on the development of auditory warnings as these are seen as being particularly strong cues. For example, flight trials have been conducted on rotor underspeed and overspeed warnings that included rotor speed rate terms (Reference 7), which were used as both engine failure warnings and as a head-up rotor speed monitor for the single engine flyaway case. In addition, Reference 8 discusses the flight tests of an early modulated tone warning. Most of these ideas would appear not to have progressed much beyond the demonstration phase, although they generally found favour with pilots. Extensive laboratory studies have also been conducted to establish the content of auditory signals, with a view to conveying the perceived urgency level and avoiding possible confusion amongst a set of auditory warnings.

Automatic intervention systems that protect rotor speed limits are not currently used on helicopters. Some work is currently ongoing and Reference 9 describes one ambitious project that aims to fully integrate an SAS, autopilot modes and navigation functions to protect the rotor speed limits. The system then further assists the pilot to perform an autorotative landing by selecting potential landing sites and providing an automatic flight path function. The approach adopted uses fuzzy logic which enables a computer system to utilise human experiences.

This fully integrated approach is seen as a long term solution that borders on the limits of current technology. For the shorter timescale applications considered here, the following section identifies possible solutions using available techniques that could be implemented on existing helicopter types.

7 SCOPE FOR PROVIDING BETTER/ADDITIONAL WARNINGS

In the course of this study, the following techniques were identified which offered the potential for improved/additional warning strategies.

7.1 Improved use of Voice Warning Systems

Voice warning devices currently fitted to civil helicopters, particularly those operating in the North sea, are not used to their full potential. These devices typically have fifteen channels, of which only a few are operative. This gives some scope for improvement at relatively low cost.

7.2 Rotor RPM Phase Advance Filter

Current audio/visual warnings for low rotor speed are triggered once the rotor speed has passed through a given threshold, normally at or slightly above the minimum normal rotor speed operating limit. The inclusion of a rotor rpm phase advance filter into the control software, could be used to adjust the position of the warning threshold by the addition of a prediction term. This could lead to warnings being issued earlier, resulting in a subsequent decrease in the rotorcraft response time.

7.3 Engine State Monitoring

Another warning method for rotor rpm loss, is through the monitoring of engine states. Following an engine failure being detected, the warning system would be able to anticipate rotor rpm loss. The detection of failures at or near to the source rather than through a symptom such as rotor speed loss, will inevitably reduce the time delay between the failure and the pilot being alerted to it.

7.4 Tactile Warnings

An additional category of warnings, not currently used on helicopters, is tactile warnings. These include stick shakers, which are normally configured to include an auditory cue, and have been used successfully on fixed wing aircraft for very many years to annunciate the onset of stall. The additional warning proposed here would act in a similar way, shaking the collective lever to indicate a low rotor speed to the pilot. The pilot would then be required to lower the lever to eliminate the shake. The effectiveness of such a system in a helicopter cockpit environment may be restricted however, due to the higher levels of noise and vibration than in fixed wing aircraft. Stick shaker systems also rely on the pilot flying hands-on, which may not be the case during cruise conditions in a multi-engine helicopter.

7.5 Direct Intervention Systems

Due to the rarity of failures that would require the pilot to take immediate action, and perhaps the lack of training or experience a pilot may have of emergency situations, it could be argued that any additional cue that attempted to marginally increase the time available to the pilot following a failure is only a small step in the right direction. To make a substantial improvement in flight safety the need to provide a rapid automatic system to aid the pilot is essential.

A direct intervention system would be configured to react automatically to protect the transient rotor speed limits. The operation of such a system may temporarily remove the pilot from the control loop and the corrective action taken, either directly via the primary control system, or indirectly through the ASE (if fitted), depending on the suitability of the latter.

8 WARNINGS AND INTERVENTION STRATEGIES SELECTED FOR ASSESSMENT

Ideally, rotor rpm warning systems should provide the pilot with the following information:

- a unique indication of a low rotor speed condition, expressing the urgency of the situation and giving the pilot sufficient time to react before the condition becomes unrecoverable,

- a head-up rotor speed monitor that can be used to control rotor speed during autorotative descents or single engine flyaway manoeuvres.

In the previous section, a range of potential warning and intervention strategies to aid rotor speed protection are listed. These were identified through consultation with pilots and specialists within WHL, external organisations and helicopter operators. From the information gained, this section identifies in more detail the features that are believed to offer some potential benefits and which have been addressed both in off-line simulation and/or in a piloted simulation trial. To investigate the performance of these enhanced warnings and to quantify any potential benefit, a Westland W30 model was selected, as this was considered to represent a typical mid-weight civil helicopter. This model has been used extensively in the off-line simulation investigations and in the piloted simulation trial and is described in Section 9.

The new features are categorised in this section in terms of the warning type.

8.1 Prediction Term

The monitoring of engine states to detect engine failure is inherently complex due to the numerous modes of failure which can occur. The number of states that would require monitoring to design a reliable and robust warning system can therefore be considerable. The difficulty of establishing a failure mode is only likely to be met through the use of a fault isolation system. This would compare a 'vector' of actual engine parameters against a model and register a failure only when the vector deviates from some predefined limits. The technique is relatively new but has been widely reported, for example in Reference 10. For an automatic intervention strategy which is required to interface with the flight control system, the detection system would undoubtedly require a high level of integrity, and hence inevitably lead to a high cost system. Engine state monitoring has therefore not been considered further in this study.

A simpler method, and one which was selected for further assessment in this study, was the phase advance filter. This method determines the rate of change of rotor rpm and then, based on this information, assesses whether the limit is expected to be transgressed.

8.2 Visual Warnings

The types of visual warnings that are issued following partial or total power failure vary enormously between aircraft types as is shown in Table 3. In the larger, twin-engine machines, some form of engine failure caption may illuminate, possibly in conjunction with a visual attention getter in front of the pilots. If rotor speed subsequently falls, this may then be followed in some cases by a further caption indicating low rotor speed. In this case the first warning should ensure that the pilot is attentive and may reduce the decision time required by the pilot once the second warning is issued. In small, single-engine helicopters, there may be no indication of engine failure/low rotor speed, resulting in a larger rotorcraft response time.

The visual warnings on the more sophisticated helicopters were generally felt by pilots to be adequate, especially if used in conjunction with an auditory warning.

An additional visual warning that would offer a possible benefit in terms of reducing the time required by the pilot to recognise the fault, would be to make the low/high rotor speed indication as obtrusive as possible, and eliminate any need for pilot interpretation. The use of the phase advance filter will also reduce the time elapsed between the failure condition and the issuing of the warning.

8.3 Auditory Warnings

The lack of commonality between manufacturers in this area is highlighted in Table 3, where the provision of auditory warnings ranges from none, through to a high level combining warnings with cautionary and advisory messages. In this study, various conflicting views have been aired by the pilots and specialists approached on the number and type of auditory warnings that should be provided. Patterson (Ref.11) suggests that a balanced set of six immediate-action warnings plus two 'attensons'[4] presents no difficulty in being learnt. Chillery (Ref.12) suggests that the time taken to memorise auditory signals increases sharply after the fifth signal.

Comments from pilots, particularly from those who fly more than one type, suggest that tones are not explicitly learnt but that, in the most extreme case, they are all

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[4] An 'attenson' is an auditory tone which is not designated to a particular failure condition, but is sounded for the sole purpose of getting the attention of the crew.

Typically, faults will be assigned to one of three priority levels, 'Warning', 'Caution' or 'Advisory'. A complex auditory warning system may have a number of discrete tones assigned to faults in the 'Warning' category, whereas attensons would group together failure conditions in the other failure categories. The attenson may be backed up by more specific information, either visually or by a voice message, detailing the failure condition.

used as a general attenson with the decision making process being based on visual diagnostic information.

Warning tones that are only heard infrequently also tend to be forgotten. In a high workload/high stress situation, such as in the case of total power failure, any effort required to identify and interpret warnings will increase the pilot's decision time.

With these comments in mind, the following general guidelines for auditory warnings have been formulated:

- the number of discrete tone warnings should be kept to an absolute minimum,

- only warnings that require an immediate pilot response should be allocated an auditory warning,

- tone warnings are more efficient than vocal messages or 'tone + message' warnings in dynamic situations where parameters can change rapidly,

- for cautionary and advisory information, a single attenson may be provided to inform the pilot that a CWP caption has illuminated.

An auditory system which appears to meet these guidelines and that was suggested by a number of the pilots approached, was to limit the auditory warning system to just two tones; one a dedicated low rotor speed warning, and the second an attenson. Voice messages preceded by the attenson could provide additional warning indications, whereas the attenson accompanied by a visual indication would provide cautionary and advisory information.

For the rotor speed protection case considered here, it was clear that the preferred method was a pure tone warning. The following warnings were therefore proposed for assessment in the piloted simulation trial:

- High and low frequency tones which are triggered once the high and low normal operating rotor speed limits, respectively, are transgressed.

- As above with the addition of the phase advance filter.

- A continuous tone whose frequency is proportional to rotor rpm. This will include the phase advance filter and only operate outside the normal operating range.

- Various modulated tones which are a function of rotor rpm and rate of change of rotor rpm.

It is acknowledged that the auditory warnings selected, namely tone warnings, are at variance to current practice that tend towards a 'tone + message' type warning. To establish the pilot's preference, a further category of warning was therefore added to the trial, namely:

- high and low rotor speed tones + messages.

8.4 Tactile Warnings and Intervention Strategies

The W30 control system (detailed in Appendix 2) offered the potential to implement a limited authority, limited speed of response, automatic intervention technique within the existing hardware. The level of authority and the speed of reaction required of a direct intervention system is very important in that it will ultimately determine the integrity, complexity and therefore cost of the system. For this reason it was proposed to determine the benefits of utilising the existing FCS as well as new systems. The aim was not to develop an intervention system for the W30, but to determine the type and performance requirements of such a system for a possible retrofit to a range of existing aircraft.

The following strategies were proposed:

- a series actuator collective pitch reducer, which would rapidly reduce collective pitch by around 10% (1·7°). This is within the series actuator authority for the W30,

- a series actuator collective pitch reducer, coupled with a 10° flare controlled by the ASE pitch attitude hold control system,

- a slow collective stick lowering system using a standard parallel actuator, (16 seconds end-to-end),

- a fast collective stick lowering system using a dedicated full authority actuator (2 seconds end-to-end),

- a collective stick shaker.

The collective stick shaker system was subsequently dropped as a test strategy following poor results from an initial evaluation. The main limitations on the stick shaker system were considered to be its general inferiority as a cue compared to an auditory warning, its ineffectiveness during hands-off flight, and the concern over using a stick shaker in an environment where a high level of vibration is typically already present.

9 MODEL DEVELOPMENT AND VALIDATION

The HEL06 helicopter simulation model developed by WHL's Advanced Engineering Department was selected for use in this programme due to its suitability for running off-line and real-time. In addition, it was already in a format compatible with the Advanced Engineering simulator selected for use in the pilot-in-the-loop trial. The model was not configured as a W30 however, the aircraft chosen for this study to represent a typical mid-weight civil helicopter, and so the first activity was to develop a W30 representation of this model (HEL0602W) (Reference 13).

An existing real-time Westland Lynx model (HEL0601L) was used as a starting point for the model development because of the Lynx's similarity with the W30 (the helicopters have similar rotor, transmission and engine systems). Fuselage and FCS routines from an existing non realtime W30 model were used to re-configure the Lynx model as a W30. Improvements to the HEL0601L rotor, transmission and engine routines have also been made without sacrificing the model's real-time simulation capability.

9.1 Model Description

The HEL0602W model is a full force and moment, six degree-of-freedom representation of a Westland 30-100 helicopter. HEL0602W contains a disc main rotor model to generate the main rotor forces and moments from the applied collective and cyclic pitch demands and a disc tail rotor to generate the tail rotor thrust from the applied tail rotor collective pitch. The resulting forces and moments are summed with those from the fuselage and undercarriage to compute the motion of the vehicle. The computer simulation also features transmission and individual engine models and a representation of a complete 4-axis flight control system including the ASE.

9.2 Model Validation

HEL0602W has been compared with flight test data gathered using G-BKKI, a W30-160 in production configuration. The aircraft was flown at 5806Kg AUM at the maximum aft centre of gravity (Xcg = –0·1676 m) and the responses to series actuator pulse inputs were recorded at hover, 85, 90, 115 and 117 knots airspeed.

HEL0602W's primary responses to these series actuator pulse inputs are close to the real W30 and most of the cross-coupling responses follow the trends of the flight data. Collective to pitch, collective to roll and yaw to roll cross-couplings are typically underestimated by 50%. There is some evidence to suggest that the transient response of the main rotor is underestimated by HEL0602W since the peak normal acceleration generated by a collective series actuator pulse input is less than expected.

Unfortunately, the W30-160 helicopter has Gem 60 engines with FADEC while HEL0602W models Gem 40 engines with a hydro-mechanical control system. Therefore, no attempt has been made to validate torque or rotor speed responses using this flight test data. Comparative tests between HEL0602W and Westland's Helicopter Airfield Performance Simulation (HAPS) model developed by the Performance Department have been carried out, however.

The HAPS model has undergone extensive validation/calibration against a detailed flight test database and is reported in various papers such as that given in Reference 14.

The two models have been compared using the time to minimum rotor speed (continuous and transient limits) following an instantaneous total power loss, and power requirements during level flight. Table 4 summarises these comparative tests for a W30-100 at 5443 kg AUM with an aft centre-of-gravity.

The table shows a close correlation between the two models' power requirements for level flight at various forward airspeeds. There is also good correlation between the two models' rotor speed decay characteristics across the speed envelope.

In preparation for the piloted simulation trial, the model underwent an assessment and subsequent calibration to enhance its handling qualities and flight characteristics, and make it more representative. This was performed subjectively during the work-up period prior to the trial commencing, and involved CAA pilots and a WHL test pilot. The modifications required included adapting the model's cross-coupling characteristics and changing ASE control gains to overcome the shortcomings inherent in the simple model used.

In conclusion, the HEL0602W helicopter model is believed to be sufficiently representative for the comparative nature of this study, with its general flying characteristics and engine-off performance following the expected trends for this class of helicopter.

Subjectively, the handling qualities and flying characteristics associated with the model, following the calibration process, were deemed to be satisfactory to meet the objectives of the trial.

10 ACTUAL INTERVENTION TIME CRITERIA

The values assigned to actual intervention time for the purpose of helicopter design and certification is a contentious issue at present, and one that is being addressed by the IAM (Ref. 15) and others. As it is primarily a human response, there is no consensus as to the appropriate value or set of values to be used. The most detailed requirements are those contained within the military defence standard (Ref 16) and are reproduced in Appendix 4 for reference.

To obtain a Type Certificate, manufacturers have to demonstrate that the characteristics of their vehicles are such that the available intervention time in the most severe operating configuration is never less than the defined actual intervention time criteria.

For UK registered civil helicopters which gained a Type Certificate prior to 1994, the requirements, as contained in BCAR Section G, Appendix to Chapter G2–8, paragraph 2, state the following:

'The transition between normal powered flight and that existing after a failure of the critical power-unit should be accomplished safely allowing for a pilot reaction time compatible with the characteristics of the rotorcraft. In no case should the delay period be less than 2 seconds when the rotorcraft is under manual control or less than 5 seconds when the rotorcraft is under automatic-pilot control. The rotor speed should not fall below the safe minimum autorotative speed during this manoeuvre, nor should it exceed the safe maximum within 2 seconds after the pilot has applied the minimum likely pitch.'

For the purposes of the off-line study, which includes investigating possible retrofit systems, the time to minimum transient rotor rpm[5] of 5 seconds is assumed for hands-off passive flight (i.e. cruise), and 2 seconds for hands-on attentive flight conditions.

It is interesting to note that both JAR–27 and JAR–29, the recently adopted European Rotorcraft codes, have wholly adopted the FAA FARs in this respect, stating:

'29.143

(d) *The rotorcraft, after failure of one engine, in the case of multi-engine rotorcraft that meet Category A engine isolation requirements, or complete power failure in the case of other rotorcraft, must be controllable over the range of speeds and altitudes for which certification is requested when such*

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5 In specifying a delay time, the regulations are directly specifying the pilot response time which the majority of pilots could be expected to react within. For the off-line study, where the pilot is absent, an easier criteria to work with is one based on the minimum transient rotor rpm.

power failure occurs with maximum continuous power and critical weight. No corrective action time delay for any condition following power failures may be less than:

(1) For the cruise condition, one second, or normal pilot reaction time (whichever is greater); and

(2) For any other condition, normal pilot reaction time.'

In this requirement 'normal pilot reaction time' is not explicitly defined. It is also noteworthy that there is no requirement for more than one engine failure in a multi-engined helicopter that meets Category A engine isolation requirements. However, the Advisory Circular material (AC29-2A) for 29.143 (d) does refer to application of the appropriate delay time to subsequent engine failures.

11 OFF-LINE EVALUATION

The potential solutions identified in Section 8 which are suitable for analytical simulation are assessed in this section purely on the quantitative benefit that they offer. The aim of this evaluation was twofold, firstly to quantify the benefits over a range of flight conditions and, secondly, to eliminate from the piloted simulation trial those solutions that offered insignificant quantitative benefits. In this way the piloted simulation trial could be constrained to a manageable size.

11.1 Reduced Rotorcraft Response Time

Current low rotor speed warning devices are triggered at or slightly above the minimum continuous rotor speed limit. Following an engine failure, the rotor speed will drop, yet the pilot will not be alerted to it for a period of time, the rotorcraft response time. This delay has the effect of reducing the time available to the pilot to take corrective action, and should therefore be minimised. One means of achieving this is by use of a phase advance filter to pre-process rotor rpm signals prior to entry to a warning/intervention system.

The phase advance filter has been used to predict the exceedance of:

- the minimum *continuous* rotor rpm (which is used to trigger the various low rotor rpm warning strategies),
- the minimum *transient* rotor rpm (which is used to trigger the various low rotor rpm intervention strategies).

The filter design represents a compromise between prediction ability and noise sensitivity. The transfer function of the filter in terms of Laplace transforms, is given by:

$$G(S) = \frac{1 + 3{\cdot}145\ S}{(1 + 0{\cdot}524\ S)}$$

Figure 1A shows the Bode plot of such a filter. The principle behind the filter's design is to detect potential transgressions of the rotor speed limits in advance of an actual occurrence. This is achieved through a combination of output gain and by phase advancing the output. The filter's operation is illustrated in the smaller plots of Figure 1A, by considering a sine wave excitation of the rotor speed at three different frequencies. The first filter response plot, at a frequency of 0·01Hz (10^{-2}) corresponds to a phase advance of 10 degrees with negligible gain. The result is another sine wave of the same amplitude but which now leads the rotor speed input signal by approximately 3 seconds. The second plot is at a higher frequency of 0·1Hz (10^{-1}) and corresponds to a phase advance of 43° and a gain of 6. Analysis of flight test traces showed that frequencies of this order of magnitude were of particular interest in power failure cases, and the filter was therefore optimised to give the maximum phase shift in this region. To avoid excessive gains at higher frequencies, however, with the consequence of initiating false warnings, the phase advance was constrained to a maximum of 45°. The third plot shows the filter's response to rotor speed excitation at a frequency of 1Hz (10^{0}). In this case the phase advance has been attenuated from its peak value of 45° to 7°, whilst the gain has continued to rise to 15. The amplitude of the rotor speed excursions now become important, as when multiplied by the gain, the predicted rotor speed can now easily transgress the rotor speed limits and trigger a false warning. Flight data pertaining to rotor speed behaviour in normal flight and following power failures was studied prior to the filter's design and great care taken in the choice of design parameters to avoid false warnings being triggered, even at the expense of restricting the filter's performance. However, the design of the filter in avoiding false indicators could only be truly assessed in the light of operational experience.

Table 5 presents the results of simulations performed using the phase advance filter to minimise rotorcraft response time as a function of torque prior to engine failure.

11.2 Off-line Evaluation of Intervention Strategies

The following four intervention strategies have been assessed as part of this study:

- a series actuator collective pitch reducer,
- a series actuator collective pitch reducer coupled with a 10° flare,
- a slow collective stick lowering system using a standard parallel actuator,
- a fast collective stick lowering system using a dedicated full authority actuator.

The first three intervention strategies could be implemented as extensions to current ASEs, while the fourth strategy would need to be an independent high integrity system. It should be noted that none of these options would be appropriate for all flight conditions. Following the assessment of the phase advance filter and the benefits seen in reducing the rotorcraft response time, this feature is included in each strategy as a standard feature.

All intervention strategies attempt either to reduce or eliminate rotor rpm decay below the helicopter's minimum transient limit (76·7%). This limit does not generally represent a physical boundary from which recovery is no longer possible, and cases where test pilots and regulatory pilots have exceeded these limits and recovered successfully are not uncommon. However, in most aircraft the transient operating range is far more restrictive than that of the W30, and expert opinion is that the 76·7% W30 limit would be very near to physical limits where blade and hub ultimate stress levels are exceeded, or rotor speed recovery is very unlikely. The minimum transient rotor speed limit for the W30 has therefore been used throughout this study to represent the minimum rotor speed from which recovery can be accomplished successfully.

Intuitively, the initial rotor rpm decay rate following an engine failure will be proportional to engine torque prior to failure. For a given AUM, engine torque is determined largely by climb rate and forward airspeed. Times to minimum transient rotor rpm have therefore been evaluated as a function of these flight parameters.

Two power loss scenarios, which are applicable to both single and multi-engine helicopters, have been examined in detail:

(a) an instantaneous total power loss – this represents the worst case scenario whereby a shaft breaks and cuts the engine's ability to supply power to the main rotor,

(b) a gradual total power loss – this represents a more probable scenario whereby fuel starvation or internal damage causes the engine(s) to run down gradually. (A time constant of 0·7 seconds is used in the simulations).

Single engine failures in multi-engine helicopters have not been directly investigated since a single engine failure will be partially compensated for by the other engine(s). In addition, as all intervention strategies are triggered by rotor rpm decay, they will be equally applicable for single and multi-engine failures.

As a baseline for this evaluation, times to minimum transient rotor rpm for the W30 were first measured without any automatic or pilot inputs. The dashed lines of Figures 2 & 3 show how engine torque varies as a function of airspeed and climb rate, and the solid lines show times to minimum transient rotor rpm (as dictated by the aircraft) for the failure scenario. (Appendix 3 gives an example of how to interpret these figures). The figures show that time to minimum transient rotor rpm is a strong function of torque prior to engine failure, and a weak function of airspeed and climb rate.

12 DISCUSSION OF OFF-LINE SIMULATION RESULTS

Table 5 summarises the performance of the phase advance filter. It has been shown to reduce the rotorcraft response time by in excess of 60% and up to 82%, depending on the torque level prior to failure and on the failure mode (gradual or instantaneous). These figures do not include any processing delays etc., and may therefore be slightly optimistic in reality.

The off-line evaluation of intervention strategies (Figures 4 – 11) has demonstrated the ability of these systems to increase the time available for the pilot to react following a total power failure. Table 6 compares the performance of the individual systems for the worst case (instantaneous total power loss) and the gradual power loss scenarios in cruise flight condition (120 knots), where the pilot is assumed to be hands-off in passive flight. The adopted criteria for the time to minimum transient rotor rpm is therefore 5 seconds (Section 10). The use of the standard series actuator with the ASE pitch input to flare the aircraft, can be seen to meet the desired intervention time criteria[6], along with the fast acting collective stick lowering system, where the minimum transient speed limit is never reached. The other systems fall well short of the desired performance, with little improvement on the baseline aircraft.

Table 7 reproduces Table 6 for the hover case. At this flight condition the pilot is assumed to be attentive and flying hands-on, and the requirement is therefore taken as 2 seconds (Section 10). For the instantaneous failure case, only the fast authority collective lowering system is deemed to have met the criteria. For the gradual failure case however, both the strategies employing the series actuator collective pitch reducer are also deemed acceptable.

The flare element introduced into one of the intervention strategies, clearly makes an important contribution to meeting the acceptance criteria at high speed. Further simulation using just a flare to control rotor speed (no collective series actuator movement), gives a time to minimum transient rotor rpm for a gradual total engine failure at 120kts of 4·6 seconds. At low speed the benefits of the flare manoeuvre becomes less significant as the magnitude of the up-flow through the rotor diminishes. It may be more advantageous in this condition to initiate a nose down pitching moment through the ASE, provided the aircraft's altitude is sufficient, to reduce the power requirements of the rotor and prepare the helicopter for entry into a forward flight autorotation.

Complete flight envelope rotor speed protection is not possible with current low inertia rotor designs following a total engine failure, where the operational avoid region exists. This region can be reduced however, to give an almost complete flight envelope minimum rotor speed protection by using a fast acting collective stick lowering system. The strategy used at low altitude would need further investigation however, as indicated in the IFEC programme and shown in Figure 1.

13 PILOTED SIMULATION TRIAL

13.1 Objectives

The primary objective of the piloted simulation trial was to make an initial assessment, both quantitatively and subjectively, of the enhanced rotor speed protection systems identified in this report. It included an assessment of the phase advance filter, an assessment of the relative merits of enhanced visual and auditory warnings in minimising the pilot's decision time, and an assessment of the effectiveness of these warnings to convey rotor speed information to the pilot. In addition, an initial assessment of automatic intervention techniques was carried out.

The quantitative assessment was effectively repeated for the automatic intervention strategies, primarily to establish how the interface between the system and the pilot affects the overall performance. The off-line studies only quantified the theoretical benefit assuming the pilot took no action. In practice if the man-machine interface is not engineered correctly, the effect of the pilot may be to reduce or even negate the benefit that could be realised.

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6 In the instantaneous failure case, 4·8 seconds was sufficiently close to the 5 seconds criteria stipulated, that this system was deemed acceptable and proceeded to the piloted simulation trial.

13.2 **Test Conditions**

Analysis of accident statistics indicates that two areas of flight operations account for the majority of 'rotor speed excursions' which lead to a reportable accident. These are: the cruise condition, where the pilot may be flying hands-off in a passive mode, and low level flight where the pilot will be fully attentive with his hands on the controls. In both cases the pilot may fail to constrain the rotor speed droop following power failure, either through a lack of time available to detect the fault and take the appropriate action, or as a result of inputting an inappropriate command. Both pilot involvement levels (hands-on in attentive flight and hands-off in passive flight) were therefore addressed in the trial.

Other factors that were considered in deciding realistic operational scenarios for the failure condition, include: the need to make the scenario applicable to both single and twin-engine helicopter operations (i.e. VFR); to take into account the limitations imposed by the simulator; and the need to limit the number of scenarios to a manageable level. Two failure scenarios were therefore chosen as follows:

Attentive flight – The twin-engine helicopter is operating OEI due to ice ingestion. The helicopter has since descended out of icing conditions and is now flying VFR, straight and level, at 90 Kts and 2000 ft prior to a second engine failure.

Passive flight – Simultaneous double engine failure in VFR, straight and level flight at a cruise condition at 120 Kts, 2000 ft, after prolonged exposure to icing conditions. The pilot is fully occupied in performing a secondary task when the failure occurs. (See A5.5 for a description of the secondary tasks).

These initial conditions were held constant throughout the trial within a small tolerance band (±5% of rotor torque), to enable results to be directly comparable across all subjects.

The pilots' involvement level at low altitude is represented in the attentive flight scenario. However, due to the limited visual cueing environment available on the simulator, this scenario was enacted at a higher altitude. Any effects that the ground proximity may have on the pilots' responses are therefore not reproduced in the simulation. Nor is there the same requirement for the pilot to select a control strategy; at low altitude the pilot would need to make a conscious decision which way to move the collective; at high altitude reducing collective is essential. These two factors together will obviously influence the pilots' intervention times and therefore the scenarios chosen may not fully represent the areas of flight operations of interest. However, these factors remain constant throughout, and in this study, where the relative performance between strategies is the main consideration, the effects of such factors are minimal.

The simultaneous double engine failure associated with the passive flight condition is an extremely unlikely failure mode, and to our knowledge, had not been encountered in any operational scenario prior to this study commencing. It was chosen as a worst possible case and also because it was analogous to an engine failure in a single-engine machine. Subsequent to the start of this trial, however, an incident to a Super Puma operating in the North Sea did occur involving a simultaneous double engine failure. This incident (Ref. 17) fortunately happened in the hover, prior to the initial climb, and resulted in a successful forced landing. However, the nature of the failure did confirm the need to take a pessimistic view.

13.3 Simulator Requirements & Hardware

The simulator chosen for the initial pilot assessment was the Advanced Engineering simulator at WHL (Ref. 18) and shown in Figures 12 & 13. This is a fixed-base simulator that is based around a Westland W30 cockpit mock-up and can be driven by the HEL06 computer model.

To accurately represent the helicopter flight environment, the simulator should ideally be able to provide all of the cues and warnings that the helicopter would provide, namely:

- External noise and auditory warnings
- Kinaesthetic cues (motion)
- Visual cues (outside world + cockpit instrumentation)

The following sub-sections detail how the limitations of the simulator were overcome or minimised for this trial through further simulator development and by careful selection of the failure scenarios. The fidelity of the simulator was considered to be appropriate for the purposes of this trial, and gave an acceptable environment in which to evaluate the selected warning strategies.

13.3.1 *External Noise and Auditory Warnings*

All auditory cues and information required by the pilot were provided through the pilot's headset. This included: background noise, auditory warnings, ATC instructions and 2-way communication with the control room.

External noise can be a very powerful cue to the pilot following an engine failure, with any sound associated with a mechanical failure or a perceived change in the rotor/transmission/engine noise often being the first indication of a problem. However, this type of cue cannot be relied on for detecting all engine failure modes, and can be indistinguishable on some helicopter types. It was therefore proposed not to attempt to reproduce any variation in the background noise that may cue the pilot to a failure condition. To add to the realism of the scenarios, however, a constant noise level, based on recorded cabin noise in a Lynx helicopter at 120 Kts cruise flight, was provided through the pilot's headset. (The Lynx has a similar drive train, gearbox, engines and rotor system to the W30, thus providing a representative noise spectrum). In addition, a prerecorded tape of ATC audio was superimposed on top of the background noise to further add to the realism of the cockpit environment. To add some diversity into the trial, which might otherwise have been repetitive and led to a low pilot motivation level, further ATC instructions were issued from the simulator control room for the pilot to follow. This took the form of changes in flight level and heading, but with any variation in the power setting and hence rotor speed decay characteristics being constrained within the allowable tolerance for the experiment. These additional ATC instructions followed standard procedures and were presented in a manner compatible with the prerecorded instructions.

Noise levels in the simulator were calibrated prior to the trial to give a background level at the pilot's ears of 80 dBA, a typical value for this class of helicopter. Auditory warnings and ATC calls were set at 15dBA above the background noise level.

13.3.2 *Kinaesthetic Cues*

The absence of a moving base is a limitation of the simulator which removes the kinaesthetic cues normally available to a pilot. Yaw motion is often an early indication to the pilot that engine power has been lost, but the only indication of yaw motion in the simulator is provided by visual cues, both from the head-down displays and from the outside world. However, flying VFR, it was believed that the perception of the yaw motion provided by the outside world would dominate the kinaesthetic cues to a large extent, and hence the absence of motion would not be significant. In manoeuvring flight, kinaesthetic cues are usually only important in aggressive flying tasks as the pilot will tend to be over aggressive without them. In this trial non-aggressive operational civil flying was being simulated with normal 'rate-one' turns (3°/s) being stipulated.

13.3.3 *Visual Cues*

The instrumentation fit on the simulator consisted of the primary instruments plus as much of the standard instrument fit as possible to add to the realism of the cockpit environment, and to provide diagnostic information (Figures 12 & 13). The primary flight control instruments were provided on a CRT display that used a unique display format. This display format followed conventional display philosophies, but was equally unfamiliar to all subjects. This ensured that no group of subjects had any advantage due to familiarity with the instrument set up.

The power systems display, which included: engine, rotor and hydraulics information, was provided on a separate CRT display. It was formatted as a series of strip gauge instruments with different coloured bands indicating normal operating ranges and transient limits. A digital readout of absolute value was also indicated above each strip gauge. The choice of this display format was made purely on the grounds of availability. Although strip gauges are not in general use on production aircraft at present, they are becoming common on the latest generation of helicopters.

Visual warning lights indicating failure conditions were provided to the pilot on the CWP and overhead fire control panel. The master caution visual indication was removed from the trial as this represented a further variable that many aircraft types do not have fitted, particularly in the light single-engine category.

The outside world was generated by a Silicon Graphics workstation and projected on a screen in front of the pilot, giving a 60° x 40° field of view. The simulator was housed in a darkened laboratory in order to maintain adequate contrast for the projected outside world view, and the scenarios selected accordingly. Some additional internal cockpit lighting was provided for video monitoring purposes and to enable pilots to perform operational tasks during the sorties. Internal reflections were minimised to prevent any undue distractions to the pilots.

13.4 Details of Warning Configurations

Each of the warning strategies used in the trial is detailed in this Section and summarised in Table 8, along with the form of the dummy warnings used to maintain a balanced warning set. Each enhanced feature has been incorporated into a warning strategy that was considered appropriate for a given technology level, with each strategy being designed such that only one feature changes between it and its corresponding datum strategy. The effect of that feature can therefore be easily identified.

All of the enhanced strategies (except the Baseline system) had the phase advance filter incorporated as standard. This raised some concern as its effects may not have been consistent across all features. However, this effect was generally thought to be of a second order nature and could not be assessed during the trial due to the constraints of time and cost.

The phase advance filter in each enhanced strategy was only active for the initial drop in rotor rpm following total power failure. Test pilot evaluation during the work-up period demonstrated that continuous functioning of the phase advance filter could lead to pilot disorientation during subsequent recovery and in controlling rotor speed during autorotation. This was due to the warnings issued by the system and the pilot's responses becoming out of phase.

13.4.1 *Baseline*

The Baseline configuration was chosen to consist of currently used warning systems, with particular emphasis being given to those fitted to small/light helicopter types. A review of the warning features fitted to various helicopter types (Table 3) showed that a representative baseline configuration should consist of a visual indicator on the CWP to warn of low rotor rpm, fire and hydraulics fault, together with a single auditory tone as an additional low rotor speed warning (N.B. No high Nr warning is provided). This represents the lowest certification standard for rotor speed warnings as outlined in JAR 27.33 and JAR 29.33.

13.4.2 *Baseline + Prediction (Pred)*

This strategy was introduced to confirm the effect of the phase advance filter identified in the off-line studies, and to give some insight into any operational aspects associated with the discrepancy between the instrumentation and the auditory warning.

13.4.3 *Multitones (Mult)*

This feature was included to quantify the effects of increasing the number of auditory warning tones by comparing the results with 13.4.2 above. It had been suggested during consultation with pilots that increasing the number of tones is a detrimental step, and can lead to increased decision times as the pilot action is no longer a reflex action, but one requiring some cognitive effort.

This system was used as a further datum strategy against which the performance of the remaining enhanced features, detailed in Sections 13.4.4–7 were compared.

The auditory warnings developed and validated at DRA(F) for the Merlin EH101 helicopter, and which are currently proposed for the civil variant, were used as the basis for auditory warnings used in the trial. This set consists of six 'tone + message' warnings of which four were used: 'low rotor speed', 'high rotor speed', 'hydraulics failure', and 'fire'. The message element of the warning was removed for this strategy. The warning was continuous and persisted while the fault condition remained.

13.4.4 *Enhanced Visual (ENV)*

If multiple tones are a prescribed feature of more sophisticated helicopters, then additional cues may be required to try to facilitate the thought process and help the pilot confirm a diagnosis. For this strategy a dedicated visual rotor speed warning was provided in an obtrusive position to give an unambiguous indication of high or low rotor speed, and the corrective action necessary.

The visual enhancement works in a similar way to a master warning/ caution caption (low rrpm=warning=red; high rrpm=caution=amber), but was dedicated to the low/high rotor speed condition. It was installed on the simulator in a prominent location on the instrument panel in front of the pilot. The low rpm indication was marked with a downwards pointing arrow indicating the low rpm as well as the direction of the collective input required. The high rotor speed indication was marked with an upwards pointing arrow for the converse case.

13.4.5 *Tones + Messages (T + M)*

Another means of unambiguously identifying audio warnings, and which has found favour with a number of helicopter manufacturers, is to follow the audio tone with a message to identify the fault. This strategy, therefore, took the basic tones of the Multitones strategy and annotated each with a prescribed explanatory message. The rotor speed warnings were coded so that they would repeat every five seconds if the pilot elected to maintain a rotor speed level that was outside the normal operating limits. In line with the developed EH101 auditory warnings, the high and low rotor speed tones were associated with the single message 'ROTOR', i.e. no specific message identified whether rotor speed was high or low, only the tone could be used to discriminate between the rotor speed conditions.

13.4.6 *Modulated Tone (Mod)*

The use of an auditory tone that mimics or enhances the noise of the rotor system was thought to offer great potential in signifying the level of urgency of the rotor speed problem. Being a 'dynamic tone' it was also felt to be easily distinguishable from any other auditory warnings that may be present which would lead to a reduction in the pilot's decision time.

This type of cue was also seen as being particularly beneficial in controlling rotor speed during autorotative descents. It gives a continuous indication of the rate of change as well as actual rotor speed while the pilot may be concentrating on other tasks such as attempting to restart an engine, or looking outside the cockpit to select an appropriate landing site.

Various modulated tones or trendsons[7] were considered for inclusion in the trial; some based on previously developed tones, others developed from WHL's own conceptions of the information which needed to be conveyed and the form that it should take. However, time and manpower constraints ultimately dictated that a modulated tone which had already largely been developed was selected. Fortuitously, modulated tone warnings for a number of parameters, including low and high rotor speed, had already been developed by Plymouth University under Contract to DRA(F), and had been validated in the laboratory. The low and high rotor speed trendsons were therefore selected for assessment in this trial. The characteristics of these trendsons, detailed in Reference 19, change in both pitch and pulse repetition rate in a stepped manner as rotor speed changes. Five levels are used, with each successive level increasing in perceived urgency the further the rotor speed strays from its normal operating condition. The characteristics of the trendson between high and low rotor speed are significantly different and are designed to mimic the change in the background noise that is often present in these circumstances. For the low rotor speed trendson, two possible analogies were suggested in Reference 19. The first used a decreasing pulse repetition rate to convey the drooping effect of the rotor, with increasing pitch being used to communicate urgency. In a preliminary assessment prior to the trial, this combination was not favoured by either of the two pilots involved. Instead the alternative trendson was selected which reversed the parameters to give an increasing pulse repetition rate for urgency, and reduced pitch to represent the decreasing rotor speed.

It was not the intention to optimise the trendson in this trial, but only to assess the technique per se. Pilot comments in the work-up period prior to the trial, however, indicated that the trendson would benefit from further urgency cues. This was implemented by adding volume modulation. As the trendson stepped to a higher level, indicating a worse situation, the volume would increase. If the trendson was stepping down a level, a larger step change reduction in volume was encoded. In this way, the sense of urgency was greater if the situation was bad and getting worse, whereas, if the pilot had responded and the rotor speed was bad but getting better, the urgency level diminished.

Reference 19 suggests that a trendson should not be used as a warning, but only in an advisory capacity to give the pilot some feedback of the monitored variable. A trendson would normally be augmented by an additional auditory warning if a critical limit was approached. However, as operation in the transient rotor speed band should be avoided wherever possible, pilot opinion was that the trendson alone gave ample indication of the rotor speed and the urgency of any action required, and that any further warning was not necessary or even desirable. The trendsons implemented in the trial were therefore not enhanced in any way by the addition of a critical limit warning.

To minimise changes in the auditory tones that were presented between strategies, the lowest level of the trendsons were substituted for the tone element of the low and high rotor speed warnings in all the audio warnings.

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7 A 'trendson' is a trend indicating sound which changes in character to convey the direction and rate at which a parameter is changing.

13.4.7 *Automated Intervention*

The Multitone strategy was enhanced by the addition of automatic intervention techniques. Two such techniques had been demonstrated in off-line simulations to be appropriate for rotor speed control and had increased the available intervention time following total power failure. These automatic techniques comprised the following:

- Auto 1 – a series actuator collective pitch reducer (10%) coupled with 10° flare (which is controlled via the ASE pitch attitude hold control system),
- Auto 2 – a fast collective stick lowering system using a dedicated full authority actuator (2 seconds stop-to-stop time).

13.5 **Experimental Design**

Full details of the pilot-in-the-loop experimental design are contained within Appendix 5.

14 **RESULTS OF THE PILOTED SIMULATION TRIAL**

14.1 **Objective Results**

Figure 14 summarises the objective results. It shows the mean rotorcraft response time, mean actual intervention time, mean available intervention time and automatic system response time for each strategy, under both attentive and passive flight conditions. Also shown, is the mean minimum rotor rpm achieved with each strategy.

The data presented in this figure is tabulated in Table 9. It is interesting to note that in the somewhat unreal environment of the simulator, where the pilot is expecting a failure and an optimistic result would consequently be expected, the pilot response times are significantly greater than 1 second for the passive flight scenario. (The pilot response time associated with the Baseline Strategy should be ignored in this comparison as the data is corrupted by the influence of the strip gauge instrumention – see discussion in Section 15.1). This result tends to confirm the optimistic nature of the JAR and FAR regulations governing pilot delay time, and also questions why the regulations take no account of the pilot's level of attention. Separate analyses were performed on each of the two main dependent variables of Actual Intervention Time and Minimum Nr achieved. Results are reported below, with detailed statistical calculations presented in Appendix 7.

14.1.1 *Actual Intervention Time Data*

A repeated measures analysis of variance was conducted on actual intervention time data. This is summarised in Table 10. There was a very significant effect of attention level on intervention time, as reflected in the F statistic, signifying actual intervention time was in general slower under passive flight conditions than under attentive flight conditions.

There was also a significant effect of strategy on actual intervention time indicating significant differences in performance due to the strategy used. Further investigations were carried out to examine the significance of differences in mean scores for each strategy.

Dunn's multiple comparison of means test was performed to establish the significance of pre-determined (a-priori) comparisons. Seven comparisons were planned prior to the experiment, in order to establish the benefits of adding various technologies to the Baseline configurations. For example the Baseline system was compared with the Baseline + Prediction strategy in order to establish the performance benefit of adding the prediction algorithm. Further comparisons included: comparing the Baseline + Prediction Strategy to the Multitones strategy, to examine the effects of adding further tones; and finally, all other strategies were compared to the Multitones strategy, the second datum strategy, to examine the effects on the pilots' performance of the Enhanced Visual system, the content of auditory signals, and the automatic systems.

Tables 11 and 12 summarise the difference in total for each of 7 comparisons between mean actual intervention times for attentive and passive flight respectively. The critical differences for significance were 6·13 seconds for the attentive flight conditions and 7·35 seconds for the passive flight conditions, assuming a probability of this occurring by chance of less than 1 in 100 ($p<0{\cdot}01$). There is a significant difference between the Baseline strategy and the Baseline + Prediction strategy under attentive conditions. No further significant differences were found. Under passive conditions the corresponding comparison was shown not to reach significance. However the comparison between the Multitones strategy and Auto 2 revealed a large significant difference in favour of shorter actual intervention times with the automatic system. (For Auto 2, Actual intervention time = Automatic system response time). No further significant comparisons were found, suggesting equal performance between the strategies compared.

Table 10 also indicates a significant effect due to subjects which suggests that there were differences in the overall performance achieved by each pilot. Figure 15 plots mean actual intervention times across all strategies under both attentive and passive flight conditions for each pilot subject. The figure illustrates that individual pilots showed a consistency in response from condition to condition. Certain pilots were generally faster or slower in their responses under both flight conditions; for example, pilot 7 was slowest under both conditions and pilot 5 was fastest.

Perhaps the most interesting result is the interaction effect between strategy, and level of attention. This indicates that pilots' performance with the rotor rpm warning strategies changed depending on the scenario they were flying. Figure 16 shows that under attentive flight conditions there is a significant difference between actual intervention times for the Baseline strategy and the Baseline + Prediction strategy. However, this difference is not apparent under passive flight conditions. In addition, actual intervention times using the Auto 2 (automatic collective stick lowering) system are significantly faster than with the Multitones strategy under passive flight conditions, but not so under attentive flight conditions.

14.1.2 *Minimum Nr Data*

A second repeated measure analysis of variance was conducted on the minimum Nr data (see Anova summary in Table 13). This analysis also indicated a very large effect of level of attention on the minimum value of Nr achieved. Figure 17 illustrates that on average, higher minimum Nr values were achieved in the attentive flight scenario than in the passive flight scenario. This result was not surprising since intervention time was expected to be longer in the passive flight scenario, and because Nr decayed faster under the higher power demands of the passive flight scenario. Figure 18 shows that on all but one sortie, pilots managed to constrain Nr to above the minimum transient rotor speed limit under attentive flight conditions. However, under passive flight conditions only the automatic intervention strategies were able to ensure that all pilots preserved Nr above the minimum transient rotor speed limit.

Table 13 also indicates that there was a significant interaction between attention level and strategy. Contributing to the significance of this interactive effect is the improved performance in terms of Nr, which resulted from using the Baseline strategy under attentive flight conditions as opposed to passive flight conditions.

There was also a significant effect on the minimum Nr data due to subjects for the same reasons discussed in Section 14.1.1.

Tables 14 and 15 summarise the results of the 7 comparisons performed under Dunn's Test for attentive and passive flight conditions respectively.

The critical difference between totals required for a significant difference between strategies is 55·31% for the attentive flight condition and 61·71% for the passive flight condition. Table 14 shows that the mean minimum Nr achieved with the Baseline configuration was significantly different to the mean minimum Nr achieved with the Baseline + Prediction Strategy, the prediction system enabling better Nr retention. Automatic Intervention System 1 also showed a significantly higher mean Nr when compared to the Multitones strategy. No further significant differences were observed, suggesting that performance in terms of Nr retention can be considered equal across the remaining strategies under attentive conditions.

Under passive flight conditions (see Dunn's test summary in Table 15), the differences between the Baseline and Baseline + Prediction strategies were not significant. However, the comparison between the Multitones condition and Auto 1 strategy remained significant and the comparison between Auto 2 and Multitones also reached significance. This suggests an improved relative performance of the Auto 2 strategy in terms of rotor speed protection in the passive flight case.

14.1.3 *Frequency of Failures*

In addition to the comparison of mean scores on minimum Nr achieved, a frequency count of the number of failures to contain Nr was performed. The failure criteria used for this analysis was transgression of the minimum transient rotor speed limit. The number of failures per strategy was logged under attentive and passive flight conditions. This is summarised in Figure 18.

Figure 18 shows that under attentive conditions only one pilot on one sortie failed. However, under passive conditions the frequency of failures was greatly increased for all of the manual strategies. The frequency plot indicates that use of the automated strategies offers the best protection with zero failures being recorded. Of the manual intervention strategies, fewest failures were evident with the Baseline + Prediction strategy. This was followed by three strategies which achieved an equal failure rate (Multitones, Enhanced Visual and Modulated Tone), whilst the Baseline and the Tones + Messages strategies performed the worst.

14.1.4 *Time To Minimum Collective*

To allow comparison with concurrent work on intervention time being performed by the UK RAF Institute of Aviation Medicine, further examination of the results included determining the mean time to minimum collective position for each strategy. This data is illustrated in Figure 19, which shows the mean time to minimum collective for each strategy under both flight conditions, as well as the distribution of scores for each strategy.

No further analysis has been performed using this data.

14.1.5 *Practice Effects*

Figure 20 indicates actual intervention time data for all 13 pilots in their first sortie and in the final sortie practice check, where they were exposed to the same intervention strategy. A shaded bar region indicates that a pilot has improved in performance on his final sortie when compared to the first sortie (i.e. actual intervention time has improved). The results illustrated in this figure are inconclusive. However, the scatter of results suggests that the randomisation approach adopted in the experimental design eliminated the effects of practice from the trial.

14.2 **Questionnaire Results**

An analysis of the data contained in the pilot questionnaires is presented in this section. Where appropriate, reference is made to figures illustrating the distribution of pilot ratings for each strategy, and a summary figure indicating the mean and median scores for each strategy. Pilot ratings were scored out of 7 with 1 being very poor and 7 being excellent. Each question was analysed using Friedman's Analysis of variance by ranks. The results of the analyses are presented on each figure; detailed data and copies of the questionnaires are given in Appendix 8.

14.2.1 *Question 1*

'Give an overall rating for the rotor speed loss warning strategy seen in this sortie under attentive flight conditions.'

Results relating to question 1 of the post sortie questionnaire are illustrated in Figure 21. Statistical analysis suggests pilots showed significantly different preferences for the 8 strategies seen in the trial under attentive flight conditions. From examination of Figure 21 it appears that the overall most preferred strategy was Auto 2, the automatic collective stick lowering system, which had on average a rating of 5·85. Baseline + Prediction, Tones + Messages, Enhanced Visual and Modulated Tone were all rated approximately equally whilst Baseline was rated worst at 4·15 on average.

14.2.2 *Question 2*

'What was the first indication that you were aware of that indicated you had a problem under attentive flight conditions?'

Pilots' responses were classified into 6 categories. The categories were; audio signals, strip instrument indications (Gauges), Enhanced Visual flashing attention getters (ENV), a combination of audio and visual cues (Aud/Vis), Others and Don't Knows. The results are summarised in Appendix 8. The data indicates that under attentive flight conditions the most prominent indications of failure recalled by the pilots in most strategies were the strip gauge instruments and the audio tones.

14.2.3 *Question 3*

'Was low Nr immediately and uniquely identifiable from the first warning under attentive flight conditions?'

The results summarised in Appendix 8 show that for each strategy, and in the majority of cases, the warning issued was uniquely identifiable as a low Nr warning. In the Tones + Messages and the Auto 1 strategies, 3 and 4 pilots respectively, reported that the warning was not uniquely identifiable. No reasons were offered by pilots for the lack of distinctiveness of the Tones + Messages strategy. With the Auto 1 strategy however, 2 pilots reported that it was not until the audio tone sounded that they could confirm that they had a rotor speed problem. A third pilot said he had to confirm his diagnosis by reference to the Nr gauge.

14.2.4 *Question 4*

'Give an overall rating for the rotor speed loss warning strategy under passive flight conditions.'

Figure 22 illustrates pilot ratings for question 4. Statistical analysis suggests a less significant effect of the strategies on the pilots' performance than under attentive conditions. From Figure 22 it appears that the automatic intervention strategies were rated highly, (on average Auto 2 was rated at 5·92, Auto 1 at 5·46) while the Baseline system was again rated as the poorest strategy (mean = 4·08). However, there are fewer differences in pilot opinion about the remaining manual strategies which were all considered approximately equal.

14.2.5 *Question 5*

'What was the first indication that you were aware of that indicated you had a problem under passive flight conditions?'

Commonality enabled pilot responses to be classified into 6 categories, as discussed in 14.2.2 above. These results are summarised in Appendix 8. The results show that with each strategy (except for the Baseline), the majority of pilots reported that the first indication of rotor speed decay of which they were aware was through the audio channel. In the Baseline condition, however, the majority of pilots reported that even under passive flight conditions the first indication noted was the movement of the strip gauges on the power systems display.

14.2.6 *Question 6*

'Was low Nr immediately and uniquely identifiable from the first warning under passive flight conditions?'

The results summarised in Appendix 8 show that, in the majority of cases, for each strategy the warnings issued were uniquely identifiable as a low Nr warning.

14.2.7 *Question 7*

'At any time did you find features of the low rotor speed warning strategy annoying, intrusive or distracting.'

Question 7 was aimed at discovering if any of the strategies were considered annoying, intrusive or distracting. The results demonstrate that on the whole most pilots found the strategies acceptable in this respect.

No pilots reported any intrusive, annoying or distracting features with the Modulated tone strategy. However, problems with other strategies were highlighted; for example, one pilot felt that the tone used in the Baseline and Multitone strategies was good at getting his attention but soon became irritating during the descent. This view was repeated by two other pilots who commented on the distracting nature of the tone during the autorotative manoeuvre.

One pilot commented that the voice component of the Tones + Messages strategy was initially useful but subsequent repetitions were distracting. A second found the warning distracting as it required confirmation of whether the Nr was high or low.

Aspects of the Enhanced Visual strategy were considered distracting or annoying by 4 pilots. One pilot expressed that he considered the flashing lights to be more of a distraction than a help particularly if used in the landing phase of an autorotation.

Although 2 pilots reported the Auto 1 strategy to have annoying/distracting characteristics, neither offered satisfactory explanations as to why this was.

During the post trial debrief session, an interesting point was raised by one pilot on the merits of the Auto 2 strategy. He reported this strategy as being distracting as he was not sure when to intervene following the automatic lowering of the lever. This could be put down to a lack of familiarisation with the system, or may indicate that additional cues are necessary.

14.2.8 *Question 8*

'Rate the strategy for aiding rotor speed control in autorotative flight.'

The results from this question are summarised in Figure 23. The statistical analysis indicates that a highly significant effect due to the strategies on pilot ratings exists. The Modulated Tone strategy had the highest mean rating (5·92) of all the strategies, with all pilots rating this system in the top half of the scale. Next highest rated was the Enhanced Visual strategy with a mean rating of 5·31. The Baseline strategy was considered the poorest strategy with a mean rating of 3·77. While the Modulated Tone strategy offered great potential in aiding rotor speed control, some pilots suggested improvements which could be made. This included: the need for better rotor speed rate information and to make the tone continuous rather than the 'stepped' implementation used.

14.2.9 *Question 9*

'At any time during the sortie were you aware of any discrepancies between the displays and the rotor speed warning strategy?'

Only one instance of a discrepancy between the displays and a rotor speed warning strategy occurred in the whole trial. This discrepancy was noted by pilot 12 using the Tones + Messages strategy who noted that the voice portion of the warning was still being presented after Nr had recovered to an acceptable value (i.e. within the green band).

14.2.10 *Question 10*

'At any time during the sortie was there any confusion associated with the low rotor speed warning?'

Five instances of confusion with the strategies were reported in the trial. These are summarised in Appendix 8. The majority of pilots reported no confusion with any of the strategies. The cases of confusion reported were related; they all involved confusion due to the similarity of the tones used for fire, hydraulic and rotor speed failures. One pilot reported that the automatic collective pull-down strategy had left him confused as to whether he should react against it.

14.2.11 *Question 11*

'Rate your level of satisfaction with the voice component of the rotor speed warning.'

This question was only relevant to the Tones + Messages strategy. The results in Appendix 8 show that on average the voice component of this strategy was considered neither satisfactory or unsatisfactory, with the pilots giving it a mean rating of 4·69.

A second part to the question asked pilots to describe the ideal specification for the voice component of such a strategy, with the main comments summarised as follows:

- four pilots considered that the voice message should distinguish between high and low Nr limit exceedance,
- one pilot considered the repetition of the rotor message distracting,
- three pilots considered the pitch of the voice component to be inappropriate; two of these thought that the voice used was too 'shrill' or high pitched; a third pilot thought that a higher pitched voice was required to instill a greater sense of urgency,
- one pilot considered the voice message to be completely unnecessary.

14.2.12 *Question 12*

'Give an overall rating for the rotor speed warning strategy seen in this sortie under both attentive and passive flight conditions.'

The results, presented in Figure 24, reveal a significant effect on the pilots' overall ratings of the strategies. The mean scores suggest that the Auto 2 strategy was considered the best (mean = 5·62), closely followed by the Modulated Tone strategy (mean = 5·46). The least preferred strategy was the Baseline system, which on average pilots rated at 3·69.

14.2.13 *Question 13*

'Do you feel the strategy seen in this sortie could be improved in any way?'

The results shown in Appendix 8 show that the body of opinion was that each of the strategies presented had room for improvement. According to the number of pilot comments, the strategies requiring most improvement were: Baseline, Baseline + Prediction, Multitones and Tones + Messages, each with 11 out of 13 pilots recommending improvements. Fewest improvements were suggested for the automatic strategies, with 3 pilots indicating that they were satisfied with the Auto 1 strategy as presented and 4 pilots for the Auto 2 strategy.

A second part to the question asked the pilots to list their recommended improvements for each strategy. These improvements are listed in Appendix 8.

14.3 Final Questionnaire

The final questionnaire was completed by pilots during the post trial debrief session. It was aimed at gauging the pilots' overall views of the trial, how representative it was, and whether the simulator impaired their performance in anyway. In addition, pilots were asked to rank the strategies seen in the trial relative to one another in order of preference, and to comment on the strategies or suggest additional techniques which they would like to see.

14.3.1 *Section A – Question 1*

'How realistic do you rate the simulation?'

This question asked pilots to rate the realism of the simulation on a five point scale, from not at all realistic (1) to extremely realistic (5). The results are summarised in Appendix 8. They show that the pilots' mean rating was 3·69. which in overall terms would seem to indicate that pilots found that the simulation had an acceptable degree of realism.

Particular aspects of the simulation which were felt to be limiting included:

- the lack of familiarity by pilots with the W30 control system, namely the auto-trim system. This resulted in some pilots having to adopt an unusual flying technique,
- the restricted outside world visual cues,
- the lack of a variable external noise cue, which although was deliberately left out in this trial, would normally be expected from the majority of helicopter types.

14.3.2 *Section A – Question 2*

'How appropriate were the tasks?'

Pilots were asked to rate the appropriateness of the tasks used in the trial for the evaluation of the enhanced rotor speed protection strategies. Pilots' average rating of the tasks was 4·08 out of 5 with no pilot feeling that the scenarios were inappropriate.

14.3.3 *Section A – Question 3*

'Did the simulator impair your performance in any way?'

Pilots' opinion as to whether the simulator had impaired their performance was split almost 50/50. Seven pilots reported no effects on their performance due to the simulator, while six pilots felt the simulator's characteristics had impaired their performance to some degree.

Principle reasons for impaired performance cited by the pilots included the poor handling and mechanical characteristics of the simulator. This was cited by 3 pilots, 2 of whom complained that they had to fly the aircraft via the 'beep trim' control which they had found unrealistic and distracting. Two other pilots cited the lack of realistic ambient helicopter noise in response to an engine failure as a contributor to impaired performance. Others considered their lack of familiarity with the system to be a limitation (2 pilots).

14.3.4 *Section B – Question 1*

'Indicate your order of preference for the rotor speed warning strategies presented during this trial.'

This question required pilots to make a forced choice judgement, placing the strategies in their order of preference. Figure 25 shows the pattern of pilot responses. The statistical analysis indicated that there is a highly significant effect, showing that pilots had significantly different preferences for the 8 strategies seen in the trial. On average the Modulated Tone strategy was ranked as the best strategy (median = 7, mean rank = 6·77). The automatic collective stick lowering system was ranked on average second (median = 7, mean rank 6·15), with the Automatic Flare manoeuvre being ranked on average third (median = 7, mean rank 5·77). The Baseline system was considered the poorest system (median = 2, mean rank = 1·85).

14.3.5 *Section B – Question 2*

'Given a free choice, describe your ideal low rotor speed warning system.'

A list of pilot comments is contained in Appendix 8.

15 DISCUSSION OF PILOTED SIMULATION TRIAL

15.1 Quantitative Results

Table 11 indicates that, in the attentive flight condition, the only feature that significantly reduced actual intervention time was the phase advance filter. This feature was shown in the off-line studies to reduce the rotorcraft response time and hence enable the various warnings to be triggered that much earlier. In the passive elements of the trial, it would have been expected that a similar result would be attained. However, this was not so, and although there appears to be a small reduction in actual intervention time due to the prediction term (Figure 16) this was not shown to reach significance. This is believed to be due to the influence of the strip gauge instrumentation. Although the subject pilots were fully occupied performing a secondary task in this phase of flight, the urgency that was conveyed by the amount of movement on the strip gauge, as perceived by the pilots' peripheral vision, was sufficient to cue them that a failure had occurred. On occurrence of a double engine failure, the power systems display would show a rapid and concurrent reduction in Ng, Nf, fuel flow and T6, closely followed by a reduction in Nr. (9 indicators in total). This may also have had an influence in the attentive flight element, but being OEI the amount of movement on the gauge was halved.

It was noted during the trial that the subject pilots positioned their secondary task paperwork in different positions. This was an interesting point in itself, but is considered here as having a possible bearing on the pilots' peripheral view. In reviewing the video tape records and comparing the actual response time with the position of the secondary task, no direct relationship was seen to exist. The variation in actual intervention time is more a function of what the pilots do with the task once the failure is recognised, i.e., whether they could respond quickly by maintaining hold of the task with their right hand while operating the collective with their left, or whether their response was delayed by the pilot opting to discard the task completely before attempting to respond.

Table 12 shows that the Auto 2 strategy produced a significant reduction in actual intervention time in the passive flight phase. This was, without exception, the system and not the pilot responding to the failure condition. In attentive flight this did not have the same level of significance as the system and the pilots' responses tended to coincide.

The effectiveness of each strategy in assisting the pilot to constrain rotor speed to within the minimum transient limit is shown in Figure 18. Table 15 also indicates that in the passive flight phase, both automatic systems are seen to be significantly different from the Multitone strategy, maintaining rotor speed above the minimum transient limit and resulting in no failures. In the case of the Auto 2 strategy, this is achieved purely by the reduction in actual intervention time. Auto 1 achieves the same result by putting in a flare manoeuvre that reduces the rotor speed decay rate and therefore increases available intervention time. In the attentive flight scenario the phase advance filter is again seen to provide a significant enhancement along with the automatic flare strategy (Table 14).

15.2 Discussion of Subjective Data

Question 8 (Figure 23) reveals that pilots had quite strong opinions of which strategies provided the best performance during autorotative flight. It seems that the Modulated Tone was particularly well liked as it provided continuous feedback of rotor speed status throughout the autorotation. The Enhanced Visual strategy also seems to have advantages for rotor speed control during autorotative flight. The addition of the flashing attention getters/collective movement directors seems to be rated as an improvement over purely auditory tones such as the Multitone condition. However, the nature of the trial, utilising dusk scenarios, may have benefitted this strategy. Visual cues in daylight conditions may not be so effective.

The relatively poor rating of both the Baseline and Baseline + Prediction strategies for aiding rotor speed control during autorotative flight may be due to the fact that neither of these strategies contained warnings for high Nr, whereas all other strategies included such warnings. The low ratings given to the Tones + Messages strategy might have been influenced by the poor cues given by this system, and the confusion associated with the same repeating 'rotor . . . rotor' message for both high and low Nr conditions.

From Figure 25, the overall ranking of the various strategies indicate the underlying pattern seen in the rest of the results. That is, the Modulated Tone strategy and the Automatic Intervention strategies were the most highly rated on average. There then seems to be a plateau in the average ranks with Baseline + Prediction, Multitones, Tones + Messages and the Enhanced Visual strategy all being considered roughly equivalent. This may be due to the fact that they all used basically the same set of tones and, to the pilots, may not have been easy to differentiate, whereas the Modulated Tone and Automatic Intervention Strategies were quite obviously different. It is interesting to note that while pilots generally rated both of the automatic systems highly in the scenario questionnaires, in the final relative comparisons some pilots marked these systems down. This was considered to be because the pilots, when comparing the systems, took account of implementation concerns and, in particular, the perceived problem in terms of integrity and reliability of automatic systems.

15.3 Comparison of Subjective and Quantitative Data

Table 16 attempts to compare the quantitative data of Figure 18 with the subjective medians contained in Figures 21 & 22, to give an overall indication of the enhanced strategies' effectiveness in aiding rotor speed protection immediately following a total power failure. To achieve this, a set of qualitative criteria have been defined as follows:

Good – Minimum Nr values from all subjects are above the minimum Nr transient limit.

Fair – The mean minimum Nr reached is above the minimum Nr transient limit although the range of minimum Nr values transgresses the limit.

Poor – The mean minimum Nr is below the minimum Nr transient limit.

Table 16 shows that the subjective and qualitative views tend to follow the same trend with the Baseline strategy being worst, the enhanced pilot cues all tending to be roughly level, followed by the automatic systems that come out best. It is interesting to note that there is very little difference between the pilot ratings for the attentive and the passive conditions. This was probably because in most cases the pilot was unaware whether he had successfully recovered or not. Although the pilot would be monitoring the rotor speed gauge during the failure scenario, the simulation model was set up so that Nr could be recovered, even if the limit was transgressed. In most cases, the rotor speed was out of limits for a very short time and therefore could either be missed by the pilot, who was trying to monitor a number of instruments concurrently, or more likely, failed to register the absolute value.

15.4 Worst Pilot Philosophy

The results and discussion so far have concentrated on the mean or median values. In statistical analysis this is the normal approach taken to eliminate the effects of individual subject's variability. This approach, however, has shown that many of the strategies used in this trial did not produce significantly different results. There is a school of thought that suggests that systems should be designed to take account of the abilities of the least able pilot. Another approach that could be adopted is therefore to look at the worst performance by a pilot using each strategy.

Figure 16 shows that there are two pilots who consistently had the longest actual intervention times. Factors that may account for this, such as the dislike of simulators, the lack of simulator experience, or negative views about the simulation trial or how it was conducted, could largely be eliminated from the information gathered in the various questionnaires. The longer intervention times appear to be a function of the pilots' adopted techniques and their relative lack of responsiveness. Figure 26 reproduces Figure 16 with this approach shown. In both the attentive and passive cases, the Multitone strategy has a greater detrimental effect, increasing actual intervention times for the worst pilot by up to 30% over the single tone used in the Baseline + Prediction strategy. This was not unexpected, as it was considered that including additional tones would involve the pilots in some cognitive effort to identify the tone or, failing that, in requiring the pilot to perform a diagnostic procedure.

The Enhanced Visual system and the addition of the voice message to the Multitone strategy would appear to offer only a small benefit in terms of reduced pilot intervention time. The performance of the Modulated tone strategy would appear to be inconclusive, decreasing intervention time for the passive flight condition, and increasing intervention time for the attentive flight condition. This may be a function of the content of the low rotor speed trendson, which was reported by pilots as not conveying the necessary level of urgency at initial onset.

In the Auto 1 strategy, discussions with the pilots indicated that the large increase in pilot intervention time attributed to the worst pilot in the passive flight phase, was primarily due to the pilot recognising that he no longer had to react quickly as the automatic system increased the available intervention time.

15.5 Discussion of Experimental Design

Pilot views on the trial, including the realism of the simulation and how appropriate the scenarios were to the evaluation of power failure cases were, within the limitations of the simulator itself, rated highly. Hardware limitations and the unique flight control system on the W30, with its auto-trim facility, did present problems to some pilots. This was primarily due to the lack of familiarity with the control system which resulted in a small minority of pilots altering their flying style, and resorting to a control technique that they would not normally have adopted. The effect of this on the trial results, however, was felt by the pilots concerned to be insignificant. In any case, the main dependent variable of pilot intervention time should not have been affected as, although it may have changed the pilot's flying technique, it should not have affected the pilot's initial response to the warning. There may have been some influence on the pilots' views regarding the realism of the simulation, although analysis of the final questionnaires reveals pilot opinion as being generally positive.

The prime limitation on this study was brought about by the need to restrict the trial to a manageable size and cost, while producing results that were statistically meaningful. It was also acknowledged that it would be unlikely that individual pilots external to Westland could be retained for a period of more than one day. However, the experimental design worked well in practice, eliminating any variables which may have influenced the results, and ensuring that the trial ran according to plan.

The naming of the strategies may have influenced the rating that the pilots gave. In particular, the Baseline strategy may have been rated the lowest simply because it was described as the Baseline, i.e. pilots expected that the enhanced strategies should be rated above the Baseline. With hindsight, a simple naming convention where letters were assigned to each strategy would have been preferable.

The nature of the trial required each pilot to be exposed to and learn the multiple tones during the training and practice periods. In the single tone strategies, where the tone should immediately inform the pilot of the rotor speed problem and trigger a reflex action from the pilot, the effect of this learning may have been to slow this reflex action and hence give a pessimistic indication of the single tone strategies' performance.

The briefing given to pilots specified a VFR flying task. However, in expecting a failure, it was inevitable that some pilots would scan their instruments at a far higher rate than normal, or even fly the task as if it were an IFR task. This is evident in Figure 16, where for some subjects their responses to the Baseline system are more rapid than those corresponding to the Baseline + Prediction strategy, where the phase advance filter ought to have alerted the pilot to the fault at an earlier time.

Due to the nature of any simulator trial, and the pilot's expectation of receiving uncommon failure conditions to which he has to respond, the quantitative data recorded for any manual strategy must be considered as being optimistic. However, simulation activities of this type are the only practical means of collecting this type of data. When comparing measured actual intervention times with the allowable intervention times, this limitation must be borne in mind in determining which systems would be acceptable. Where possible, data was used to rank each system relative to the others.

Pilots were not informed of their performance using any of the strategies prior to completing the strategy questionnaires. In most cases the pilots were unaware of their true performance and were therefore only able to judge the systems relative to each other based on their own performance perceptions. This was an oversight in the experimental design, as providing the pilot with an indication of his true performance, and whether the system enabled him to successfully recover, may have had a profound influence on the pilots' ratings.

It is clear from the results that the head down instrumentation provided to the pilots had a significant influence on their intervention times. This was not anticipated during the experimental design stage when other forms of instrumentation could have been provided, or the instrumentation types made a variable within the trial.

16 GENERAL DISCUSSION OF INDIVIDUAL ENHANCEMENTS

16.1 Phase Advance filter

The phase advance filter has been demonstrated to be a beneficial feature and can lead to an increase in the time available for the pilot to respond. Table 5 shows that for the passive flight scenario where the gradual total engine failure was initiated at 85% torque, the performance of the phase advance filter found in the off-line studies reduces rotorcraft response time by 0·7 seconds (1·10 – 0·43). A similar analysis for the attentive flight scenario (equivalent to 55% engine torque) reveals a result nearer to 1·0 seconds.

The pilot-in-the-loop simulation results tend to confirm the performance of the phase advance filter. The quantitative results, summarised in Table 9, indicate a mean reduction in rotorcraft response time of 1·0 seconds (1·50 – 0·58) for the attentive flight scenario and 0·8 seconds for the passive flight scenario. It should also be noted that the effect of the phase advance filter is to nearly treble the maximum available pilot response time. For the attentive flight scenario the maximum available pilot response time without the phase advance filter = 2·11–1·50 = 0·61 seconds, whilst with the filter it increases to 2·11–0·58 = 1·53 seconds. In the passive flight scenario, a similar analysis reveals an increase in available pilot response time from 0·35 seconds to 1·11 seconds with the phase advance filter. However, the savings in rotorcraft response time do not lead directly to savings in actual intervention time. Table 9 states that mean actual intervention time savings of only 0·48 seconds (attentive flight) and 0·15 seconds (passive flight) were attained. This result is a further indication of the influence of the strip gauge instrumentation and infers that the pilots were already cued to the fault prior to the specific cockpit warnings (visual and auditory) being issued. However, the influence of a visual cue may not be as strong for a conventional instrumentation display or in daylight conditions. Hence the first indication the pilot receives of a fault may indeed be influenced by the phase advance filter.

Implementation of the phase advance filter would be a relatively simple task. It would be applicable to all helicopter types, and could be installed as a retro-fit system to existing vehicles. The only input to the filter is Nr, which is readily available on all helicopters, and the output would be connected directly to existing warning devices.

16.2 Multitones

The addition of multiple tones into a cockpit environment to warn of failure conditions has not shown any significant change to the average pilot's response time. This could be construed as an advantage for this system as it indicates that more information could be made available from audio warning without affecting the pilot's performance. However, using the worst pilot philosophy, and through objective reasoning, multiple tones must involve additional cognitive effort which will inevitability result in longer decision times for at least some pilots and hence increased actual intervention times.

There is a generally accepted limit amongst academics that the maximum number of audio tones presented to a pilot should be no greater than six. Work performed in this study would suggest that this figure is not accepted by pilots, who would prefer a much lower limit.

16.3 Enhanced Visual System

It has not been possible from the results of this study to establish any significant objective benefits for this system. Subjective views tended to be split, with some pilots feeling that it did simplify the diagnostic process or acted as another confirmation of the failure condition, while others felt that it did not add anything or was more of a distraction. For control of rotor speed during autorotation, pilot opinion was again split but with the majority tending to favour the system. It was acknowledged however, that the nature of the scenarios selected, i.e. at dusk, did tend to favour this system.

The implementation of this system on a helicopter would be simple and applicable to all types. It could be driven from the existing Nr indication system, via the phase advance filter if desired. The system would, however, take up a large amount of valuable space in front of the crew. In addition, the proximity to the existing master caution lights, normally fitted on more advanced helicopters, may have a detrimental effect and become confusing to the pilot. This would need further investigation.

16.4 Tones + Messages

The Tones + Messages strategy was added to the trial to ascertain whether this type of warning was as effective at conveying rotor speed information to the pilot as pure auditory tones. The quantitative results would suggest that there is no significant effect on the performance of tone + message warnings to convey the initial failure urgency, relative to the other auditory warning types. However, the tones + messages strategy did give the worst failure rate, with all pilots failing with this system in the passive flight scenario (Figure 18).

Subjectively the Tones + Messages strategy was rated higher than the Multitones strategy. This was primarily due to the pilots preferring the message for the 'dummy' warnings ('Fire' and 'Hydraulics').

As an aid to rotor speed control in autorotation, the mean pilot ratings presented in Figure 23 show that the improvement over the Baseline strategy provided by the Tones + Messages strategy was due entirely to the phase advanced filter, and that all other strategies offered greater benefits.

Finally, it is worth noting that in the ideal system proposed by the test subjects, only four pilots suggested using any form of vocal message for rotor speed warnings, whereas a modulated tone was included almost without exception.

16.5 Modulated Tone

The Modulated Tone was found to have no significant effect on pilot performance. This was disappointing in that it was expected that, due to the uniqueness of the tone, the failure condition could easily be identified from other warning tones. This may be a function of the content of the low Nr tone, which was felt not to convey the level of urgency required in the first few levels of the trendson, and a lack of familiarity due to the pilots' limited exposure to this cue.

Where the Modulated Tone was found to be greatly beneficial was in the control of rotor speed during an autorotative descent. Pilots reported that it was possible to monitor the rotor speed without reference to instrumentation, enabling them to perform other visual tasks.

The consensus was that this strategy had great potential with, perhaps, more development of the tone's content and structure being required. Application to new and existing types is feasible and again could be used with the phase advance filter to trigger the warning sooner during the initial drop in rotor rpm following total power failure.

16.6 Automatic flare + Series Actuator Collective Pitch Reduction

The automatic flare strategy enabled the helicopter to recover from the power failure conditions set in the trial and increased the time available for the pilot to take subsequent recovery action. Further analysis at other flight conditions showed that the strategy was applicable across the whole speed range, except for the low speed and hover cases where the benefits of the flare diminish. In these conditions, another form of recovery action would be more appropriate, as would the actions from the automatic system if the failure occurred at a low height.

Pilots generally liked this strategy as it not only took the initial action and increased available intervention time, but also assisted the entry into autorotation by raising the nose and reducing speed. The absence of a motion system on the simulator would undoubtedly have restricted the cues that the pilot received from this technique, and may have influenced the performance of the strategy. However, the automatic flare strategy was felt to represent a more practical solution than the collective stick lowering system. It was seen to offer the benefit of increased available intervention time without the need for full authority control and the attendant integrity issues of a collective stick lowering system.

Implementation of the full strategy, requiring both pitch and collective inputs, would require the helicopter to be fitted with a complex ASE. This would make it only applicable to a few types and totally uneconomic for the smaller, less sophisticated helicopters. However, it has been established that the primary benefit from this system, at least at moderate and high speeds, comes from the flare component. Implementation of just an ASE flare control mode would, however, yield a greater number of potential applications.

16.7 Automatic Collective Stick Lowering System

The full authority collective stick lowering system assessed during this study, gave a full speed range low rotor speed protection system that was demonstrated to be able to cope with a worst failure condition (instantaneous total power loss). The only performance limitation of the system, as presently modelled, was the low height limitation.

With an ASE fitted and functioning, there was no need for the pilot to take any immediate action, and often the helicopter would enter a trimmed autorotative descent without exceeding any vehicle limitations. This tended to give a high rotor speed however and a high rate of descent. To achieve a more desirable autorotative profile, the pilot was required to take command and raise the collective lever.

Pilots felt this system was wholly appropriate and appreciated the improved safety benefits that it could provide. On the negative side, there was concern shown that such a system would need to have high integrity and reliability. An additional cue to alert the pilot that the system had operated was felt to be necessary, perhaps in the form of a collective position indicator.

The complexity of this system is likely to make it impractical and uneconomic to install on a retro-fit basis.

17 LIMITATIONS & FURTHER DEVELOPMENTS OF THE AUTOMATIC INTERVENTION STRATEGIES

The automatic systems developed for assessment in this trial were based upon the performance of a number of proposed systems identified in the off-line studies. The techniques chosen offered the potential to cover only part of the flight envelope and would need to be developed further to provide a full flight envelope protection system.

The performance of the automatic systems has been shown in the trial to arrest the rotor speed decay rate well before the transient rotor speed limit is reached. Further development of these systems could increase the automatic system response time, if desired, to give the pilot more time in which to intervene prior to the automatic recovery action being triggered.

Further developments to these techniques could lead to a system that eventually flies the full autorotative manoeuvre to the ground. Alternatively, additional features could be included in the system developed here; for example, to automatically set collective pitch to make use of the maximum available power in the OEI flyaway case.

18 CONCLUSIONS

18.1 Review of accident statistics

Section 3 of this report reviewed the data contained in the CAA's Mandatory Occurrence Report (MOR) database to ascertain the historical significance of rotor speed control problems on the accident record of civil helicopters registered in the UK. With the aid of expert opinion, a judgement was made on what effect an enhanced rotor speed protection system could have had on these statistics. The findings of this review are listed below:

- Reportable accidents involving rotor speed excursions are more prevalent in single-engine machines.
- The accident rate in both cruise flight and at low level flight is significant.
- 82% of all reportable accidents involving rotor speed excursions could potentially have been prevented, or reduced in severity, if an enhanced rotor speed protection system had been fitted.
- 18% (9/50) of all UK fatal helicopter accidents which occurred between 1976 and July 1993 could potentially have been prevented, or reduced in severity, by the use of an enhanced rotor speed protection system, with a potential saving of 29 lives.

18.2 Review of current warnings and procedures

Before attempting to postulate new ideas, a review of current warning systems and procedures was undertaken. The objective was to determine whether any consensus in warning strategy was evident, and whether any current warning system showed any distinct advantages in the protection of rotor speed. The main findings are listed below:

- The rotor speed warning systems fitted to current helicopter types are varied, with little common ground between manufacturers. (Ref. Table 3).
- No correlation between the accident data and the type of rotor speed warning configuration fitted to helicopters could be established in this study. (Ref. Section 4.5).

18.3 The scope for providing additional warnings

Section 2 has identified a number of possible areas where current rotor speed warning systems could be enhanced. These are:

- reduced rotorcraft response time, through improved state monitoring,
- reduced decision time, through the use of improved warnings provided to the pilot,
- increased available intervention time, through the use of intervention techniques designed to automatically detect engine failure/rotor speed loss and take appropriate action,

- improved pilot awareness of rotor speed during autorotation, through the adoption of an appropriate warning strategy.

Section 7 details some ideas as to how these improvements could be achieved.

18.4 The enhanced warning strategies

Various enhanced rotor speed protection systems have been postulated and assessed in this programme, which comprised both off-line and pilot-in-the-loop simulation. The most promising systems to emerge, detailed in Sections 13.4 & 16, are summarised below:

18.4.1 *The Phase Advance Filter*

This enhancement represents a fairly simple addition to present rotor speed monitoring systems, and would provide an increase in the time available for a pilot to react by issuing warnings earlier. In the case of a gradual total engine failure (0·7 second time constant) the reductions in rotorcraft response time found in the off-line simulation (Table 5) were between 0·5–1·4 seconds, depending on the rotor's torque requirement at the time of the failure. In the two scenarios used for the piloted simulation trial, it has been established that the use of a phase advance filter can lead to a trebling in the time available for the pilot to respond to the failure. The performance was not confirmed during the piloted simulation trial however, primarily due to the influence of the strip gauge instrumentation in the dusk scenarios used and the expectation by the pilots of receiving a failure. In a practical application, where these factors would not be as influential, close to the full theoretical benefit should be achievable.

18.4.2 *Modulated Tone*

Subjectively, the Modulated Tone was given the highest mean rating of all the strategies assessed and was, without exception, deemed to be a beneficial technique by the test subjects. This was particularly evident in the control of rotor speed during autorotative descent, as the pilots were able to monitor rotor speed without constant reference to head down instrumentation. However, while the Modulated Tone warning was considered to offer real benefits, this could not be substantiated in the objective results. This may be indicative of the method of implementation of the Modulated Tone in the simulator, and/or a result of the less than optimum signal content.

18.4.3 *Automatic Flare + Series Actuator Collective Pitch Reduction*

The automatic flare + series actuator collective pitch reduction strategy offered a limited rotor speed protection capability. This strategy worked within the limits of an ASE and functioned by demanding a pitch attitude increase coupled with a series actuator collective pitch reduction. The strategy worked well in the trial, and was found to be appropriate in all failure cases except at low speed and in the worst failure mode (instantaneous total power loss). The strategy could be modified to make it applicable to more helicopter types by only considering the pitch channel input. Further developments, possibly by scheduling the nature of the input depending on flight condition, may further improve its performance and/or make it effective for all failure conditions.

Implementation of the automatic flare strategy would be limited to helicopters fitted with a suitable ASE.

18.4.4 *Automatic Collective Stick Lowering Strategy*

The automatic collective stick lowering strategy assessed in this study was a full authority, fast acting system that monitored the rotor speed and took the necessary action to protect it across the full airspeed envelope. The performance of the strategy was liked by the test subjects, with no detrimental man/machine interface problems being reported.

The system, as modelled, was only suitable for entering autorotation and would require further refinements for use at low height, where a different control philosophy would be required.

Integrity issues may make this system impractical/uneconomic for inclusion in existing helicopters, and it may only be commercially acceptable for new, high specification types.

18.5 Miscellaneous Issues

Other issues that were raised during the course of this study and that are worthy of note, are listed below.

- The requirements published by civil regulatory authorities tend to be poorly defined and lack specific and unambiguous terminology. (Reference Section 10).
- Results obtained during this study would suggest that the actual intervention time criteria specified by FAR 27/29 and now adopted by JAR 27/29 is optimistic and may not represent the real achievable performance of pilots. In addition, the requirements take no account of pilot attentiveness level which was found to have a significant effect (reference Section 14.1).
- The extent to which multiple auditory tones are applied to a helicopter cockpit environment needs to be reviewed. Some subjective evidence was obtained that multiple auditory tone warnings are not being used in the manner in which they were intended; i.e., the meanings of specific tone warnings are not retained by pilots. This may lead to the reduced effectiveness of an auditory warning in the urgent power failure case. (Section 8.3).
- The use of strip gauge instrumentation to present rotor and engine parameters was found to be effective, and following a failure, was a powerful cue to the pilot. (Reference Section 15).

19 RECOMMENDATIONS FOR FURTHER WORK

(1) The recently adopted JAR regulations governing pilot intervention time criteria following power failure should be reviewed. The delay time criteria stipulated in the JARs is considered to be a much more relaxed requirement than the corresponding BCAR, and may not reflect the actual ability of the pilot. In addition, the ambiguity found in regulations could be eliminated by the standardisation of definitions and terminology.

(2) The use of multiple auditory tones in a helicopter cockpit environment needs to be reviewed, as it is considered that these may have a detrimental effect in urgent cases such as total power loss.

(3) Implementation and demonstration of the phase advance filter should be conducted. This activity would optimise the filter design for a practical application, taking into account such constraints as the system delay time. It would also be necessary to demonstrate that such a system was robust and able to cope with normal variations in Nr without triggering spurious warnings.

(4) Optimisation and implementation of a Modulated Tone warning is required. Further development of the content of the Modulated Tone would enhance the performance of this strategy. In particular, work should focus on increasing the perception of urgency in the lower levels, following the initial failure condition.

(5) Automatic systems to provide a full flight envelope rotor speed protection system require development. Further pilot assessment of these techniques would be required, and consideration should be given to using a simulator which offers motion cues.

(6) Cost-benefit analysis and integrity studies of any proposed system are required.

(7) Further evaluation of the benefits of strip gauges to convey power system information quickly and accurately to the crew should be conducted.

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21 ACKNOWLEDGEMENTS

The authors would like to thank the following companies and individuals for their support and co-operation in connection with this study.

D Howson	CAA
D Chapman	CAA
N Talbot	CAA
K Dodson	CAA
Capt. M Fooks-Bale	CAA
Capt. B Hodge	CAA
Capt. J Ramsdale	CAA
Capt. L DeMarco	CAA
P Sparkes	CAA
Capt. N Kidd	McAlpine Helicopters Ltd
Capt. M Griffin	Bristow Helicopters Ltd
Capt. M Betts	Bristow Helicopters Ltd
Capt. N McDonald-Gibson	Bristow Helicopters Ltd
Capt. R Jones	Bristow Helicopters Ltd
Capt. M Shaw	Bond Helicopters Ltd
Capt. N Mortimer	Bond Helicopters Ltd
Capt. T Larman	Bond Helicopters Ltd
M Bounden	Sloane Helicopters
M Stalken	–
Capt. S Mold	British International Helicopters Ltd
Capt. S Finkin	British International Helicopters Ltd
Capt. D Bailey	British International Helicopters Ltd
S Mungur	DRA Farnborough
E Hay	DRA Farnborough

J Chappelow RAF Institute of Aviation Medicine

Dr J Edworthy Plymouth University

and to A Alford and N Osborne of Westland Helicopters Limited for their hard efforts in preparing the computer software and simulator hardware respectively.

22 GLOSSARY

AAIB	–	Air Accidents Investigation Branch
ASE	–	Automatic Stabilisation Equipment
ATC	–	Air Traffic Control
AUM	–	All-up-Mass
AVAD	–	Automatic Voice Alerting Device
BCAR	–	British Civil Airworthiness Requirements
CAA	–	Civil Aviation Authority (UK)
CFH	–	Carefree handling
CPL(H)	–	Commercial Pilots Licence (Helicopter)
CWP	–	Central Warning Panel
DRA(F)	–	Defence Research Agency (Farnborough)
FADEC	–	Full Authority Digital Engine Controls
FAR	–	Federal Aviation Regulations
FCS	–	Flight Control System
HAPS	–	Helicopter Airfield Performance Simulation
IAM	–	Institute of Aviation Medicine
IFEC	–	Integrated Flight and Engine Controls
IFR	–	Instrument Flight Rules
JAR	–	Joint Aviation Requirements
MOR	–	Mandatory Occurrence Report
mtbf	–	mean time between failures
Nr	–	Main rotor rotation speed
OEI	–	One Engine Inoperative
VFR	–	Visual Flight Rules
Xcg	–	position of aircraft cg along body longitudinal axis, relative to datum position
WHL	–	Westland Helicopters Limited

Tables

Table 1A Helicopter Rotor RPM Loss – Reportable Accident Data

(Data extracted from the CAA's MOR database, covering the period from 1976 to July 1993)

	HIGHLY PROBABLE		*PROBABLE*		*IMPROBABLE*		*TOTAL*		
Singles	2 2C/0L	(3%)	63 13C/50L	(80%)	13 10C/3L	(17%)	78 25C/53L	(100%)	90%
Twins	2 2C/0L	(22%)	4 0C/4L	(45%)	3* 3C/0L	(33%)	9 5C/4L	(100%)	10%
Total	4 4C/0L	(5%)	67 13C/54L	(77%)	16 13C/3L	(18%)	87 30C/57L	(100%)	100%

* 1 involving an Nr increase

C = Cruise
L = Low level

Highly probable – It is considered highly probable that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Probable – It is considered probable that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Improbable – It is considered improbable (or unlikely) that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Table 1B Helicopter Rotor RPM Reportable Accident Data – By Aircraft Type

	No On Register at 1/4/93	HIGHLY PROBABLE			PROBABLE			IMPROBABLE			GRAND TOTAL	FATALS (F)
		Cruise	Low Level	Total	Cruise	Low Level	Total	Cruise	Low level	Total		
SINGLES												
AS350	24					1	1				1	
BELL 206	120				2	10 (1F)	12	3	1	4	16	1
BELL 47	23				2	9	11				11	
ENSTROM 280	24					3	3				3	
ENSTROM F28	25					10	10	5	2	7	17	
HILLER UH 12E	3					5	5				5	
HUGHES 269	16				1	3	4	1		1	5	
HUGHES 369	23				2 (2F)		2				2	2
ROBINSON R22	201	2 (2F)		2	5 (5F)	7	12				14	3
SA341G GAZELLE	12				1	1	2	1		1	3	
WESTLAND S55	2					1	1				1	
Totals (Singles)	473	2 (2F)	0	2	13 (7F)	50 (1F)	63	10	3	13	78	6
TWINS												
AS330	0					1 (1F)	1				1	1
AS355	40	1 (1F)		1		1	1				2	1
AS365	15					1	1				1	
BELL 212	4							1 (1F)		1	1	1
BELL 214	2							1		1	1	
BO-105	20					1	1	1		1	2	
WESSEX 60	0	1 (1F)		1							1	1
Total Twins	109	2 (2F)	0	2	0	4 (1F)	4	3 (1F)	0	3	9	4
Grand Totals	582	4 (4F)	0	4	13 (7F)	54 (2F)	67	13 (1F)	3	16	87	10

(Data extracted from the CAA's MOR database, covering the period from 1976 to July 1993)

Table 2A Fatal Accidents

(Data extracted from the CAA's MOR database, covering the period from 1976 to July 1993)

	HIGHLY PROBABLE	*PROBABLE*	*IMPROBABLE*	*TOTAL*
Singles	2 2C/0L	4 3C/1L	0	6 5C/1L
Twins	2 2C/0L	1 0C/1L	1 1C/0L	4 3C/1L
Total	4 4C/0L	5 3C/2L	1 1C/0L	10 8C/2L

C : Cruise
L : Low Level

Highly probable – It is considered highly probable that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Probable – It is considered probable that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Improbable – It is considered improbable (or unlikely) that a rotor rpm speed protection system, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Table 2B Fatal Accident References

	HIGHLY PROBABLE				*PROBABLE*				*IMPROBABLE*			
	A/C Type	*Date*	*Occ No.*	*No. Fatalities*	*A/C Type*	*Date*	*Occ No.*	*No. Fatalities*	*A/C Type*	*Date*	*Occ No.*	*No. Fatalities*
Singles	R22 Beta	8/9/91	9103221	1	Hughes 369HS	6/12/89	8904846	2				
	R22 Mariner	23/2/92	9200496	2	Bell 206B	24/1/90	9000239	1				
					R22 Beta	28/3/90	9001233	1				
					Hughes 369HS	31/8/90	9003913	1				
Twins	Wessex 60	13/8/81	8102509	13	AS330 Puma	10/10/82	8202964	2	Bell 212	20/11/84	8403749	2
	AS 355	8/4/86	8600990	6								

Table 3 CWP and Auditory Warnings

This table gives a list of CWP warnings which are relevant to engine failure and subsequent rotor speed loss, for various civil helicopter types. In addition, a full list of auditory warnings which are fitted to the different aircraft types is also presented to illustrate the number and type of warnings issued and the circumstances which cause them to be triggered.

- * – Indicates first warning to the pilot of power loss
- T – Tone warning
- M – Message
- TM – Tone + Message

		ENGINE WARNINGS						ROTOR WARNINGS			
	MASTER CAUTION	*LOW NG*	*DIFF NG*	*DIFF P3*	*FUEL PRESS*	*OIL PRESS*	*ENGINE FIRE*	*LOW NR*	*HIGH NR*	*OTHER WARNINGS*	*COMMENTS*
AS330											
CWP						ENG 1 ENG 2					
AUDIO								T (HORN)			
						*					
AS332 SUPER PUMA											
CWP	ALARM		DIFF NG			ENG P1 ENG P2		NR MIN <245 RPM		ELECT – ELECTRICAL SUPPLY FAILURE OVSP – ENGINE OVERSPEED	
AUDIO								T CONTINUOUS BEEP LOW FREQ	T HI FREQ		
	*		*								FOR DOUBLE FAILURE 'NR MIN' + AUDIO MAY BE FIRST INDICATION

Table 3 (Continued)

	MASTER CAUTION	ENGINE WARNINGS						ROTOR WARNINGS		OTHER WARNINGS	COMMENTS
		LOW NG	*DIFF NG*	*DIFF P3*	*FUEL PRESS*	*OIL PRESS*	*ENGINE FIRE*	*LOW NR*	*HIGH NR*		
SA341/2 GAZELLE											
CWP						ENG P ENG.GI					
AUDIO											
						*					
AS350 SQUIRREL											
CWP	ALARM					ENG P				GEN – ELECTRICAL SUPPLY FAULT	
AUDIO								T (HORN) <360 RPM			
	*					*					
AS355 TWIN SQUIRREL											
CWP	ALARM					EN OIL PRESS				GEN – ELECTRICAL SUPPLY FAULT AUTO RE-LIGHT – ALISON ENGINES	DOESN'T DISTINGUISH BETWEEN ENGINES
AUDIO	T (N2)							T (HORN) <360 RPM			ATTENTION GETTER (N2) TRIGGERED BY RED/AMBER CAPTION ON THE CWP OR F/A CYCLIC LIMITS ARE REACHED.
	*					*					

Table 3 (Continued)

	MASTER CAUTION	ENGINE WARNINGS						ROTOR WARNINGS		OTHER WARNINGS	COMMENTS
		LOW NG	DIFF NG	DIFF P3	FUEL PRESS	OIL PRESS	ENGINE FIRE	LOW NR	HIGH NR		
SA365N/N2/C											
CWP	ALARM	PWR				ENG 1 ENG 2				GEN – ELECTRICAL SUPPLY FAILURE	
AUDIO			T (N2)					(HORN) <380 RPM			
	*	*									FOR DOUBLE FAILURE, LOW NR HORN MAY BE THE FIRST INDICATION
A109											
CWP		ENG 1 ENG 2 <60%									
AUDIO											
		*									

Table 3 (Continued)

	MASTER CAUTION	*ENGINE WARNINGS* LOW NG	DIFF NG	DIFF P3	FUEL PRESS	OIL PRESS	ENGINE FIRE	*ROTOR WARNINGS* LOW NR	HIGH NR	*OTHER WARNINGS*	*COMMENTS*
A109C											
CWP		ENG 1 ENG 2 <60%				OIL PRESS	ENG 1 FIRE ENG 2 FIRE	ROTOR RPM	ROTOR RPM		
AUDIO	M 'WARNING'	M 'ENG 1(2) LOW'				M WARNING	M 'ENG 1/ 2 FIRE'	TM 'ROTOR'	M 'WARNING'	IN ADDITION, MASTER AUDIO 'WARNING' FOR: BATTERY HOT BATTERY DISCHARGE GENERATOR HOT TRANS OIL PRESSURE TRANS OIL HOT	FOR LOW ROTOR, HEADSET VOCAL MESSAGE + CABIN TONE
		*									
BELL 47											
CWP											
AUDIO											
BELL 206 JET RANGER											
CWP											
AUDIO		T (INTER- MITTENT)						T (CONTI- NUOUS)			
		*									

Table 3 (Continued)

		ENGINE WARNINGS						ROTOR WARNINGS			
	MASTER CAUTION	*LOW NG*	*DIFF NG*	*DIFF P3*	*FUEL PRESS*	*OIL PRESS*	*ENGINE FIRE*	*LOW NR*	*HIGH NR*	*OTHER WARNINGS*	*COMMENTS*
BELL 212											
CWP	MASTER CAUTION	ENG 1 OUT ENG 2 OUT			FUEL 1 FUEL 2	OIL PRESS	FIRE 1 FIRE 2	RPM	RPM		
AUDIO											
BELL 214ST											
CWP	MASTER CAUTION ½ SEC AFTER ENG OUT CAPTION	ENG OUT ENG OUT <62%			FUEL PRESS	OIL PRESS <15 PSI		ROTOR RPM <95% RPM		BLOWER OFF	
AUDIO											
		*									
BO105											
CWP						ENG				GEN – ELECTRICAL SUPPLY FAILURE	1ST FAILURE ONLY DOESN'T DISTINGUISH BETWEEN ENGINES
AUDIO								T (HORN)			
								*			

Table 3 (Continued)

	MASTER CAUTION	ENGINE WARNINGS						ROTOR WARNINGS		OTHER WARNINGS	COMMENTS
		LOW NG	DIFF NG	DIFF P3	FUEL PRESS	OIL PRESS	ENGINE FIRE	LOW NR	HIGH NR		
BK117											
CWP		ENG 1 LOW / ENG 2 LOW				ENG 1 OIL P / ENG 2 OIL P				GEN 1 / GEN 2 – ELECTRICAL SUPPLY FAILURE	
AUDIO		TM <60%	M				TM	TM <95% RPM	M >106%	TM – 'LOW ALTITUDE' TM – 'BATTERY DISCHARGE' TM – 'BATTERY HOT' TM – 'TRANS OIL PRESS'	DC POWER FROM BATTERY >70°C <1 BAR
EH101											
CWP	$\boxed{}$	←		ENG FAIL			→	ROTOR SPEED		ELEC – ELECTRICAL SUPPLY FAILURE	HUMS 1553 DATA BUS AUTO TORQUE MATCHING 1ST FAILURE DESIGN PHILOSOPHY
AUDIO	TM 'WARNING'	←		TM 'ENGINE FAIL'			→ TM 'FIRE'	← TM 'ROTOR' →		TM – 'LANDING GEAR' TM – 'ALTITUDE 150FT'	
	*	←		*			→				
ENSTROM 280											
CWP											
AUDIO											

Table 3 (Continued)

	MASTER CAUTION	ENGINE WARNINGS						ROTOR WARNINGS		OTHER WARNINGS	COMMENTS
		LOW NG	DIFF NG	DIFF P3	FUEL PRESS	OIL PRESS	ENGINE FIRE	LOW NR	HIGH NR		
ENSTROM F28											
CWP											
AUDIO											
HILLER UH 12E											
CWP											
AUDIO											
HUGHES 269											
CWP											
AUDIO											
HUGHES 369											
CWP		<55%									
AUDIO							T	T			
		*									

Table 3 (Continued)

	MASTER CAUTION	ENGINE WARNINGS						ROTOR WARNINGS		OTHER WARNINGS	COMMENTS
		LOW NG	*DIFF NG*	*DIFF P3*	*FUEL PRESS*	*OIL PRESS*	*ENGINE FIRE*	*LOW NR*	*HIGH NR*		
ROBINSON R22											
CWP								$\boxed{}$			
AUDIO								T (HORN)			
								*			
S61N											
CWP								$\boxed{\text{TAIL T/O}}$ <97% RPM			
AUDIO							TM 'FIRE' (AVAD)				
								*			
S76A+											
CWP		$\boxed{\text{ENG OUT}}$ <66%									AT NIGHT, LOSS OF CABIN AND INSTRUMENT LIGHTING. INSTABILITY DUE TO LOSS OF AFCS
AUDIO		T ALT TONE 550/700 HZ									
		*									

Table 3 (Continued)

	MASTER CAUTION	ENGINE WARNINGS: LOW NG	ENGINE WARNINGS: DIFF NG	ENGINE WARNINGS: DIFF P3	ENGINE WARNINGS: FUEL PRESS	ENGINE WARNINGS: OIL PRESS	ENGINE WARNINGS: ENGINE FIRE	ROTOR WARNINGS: LOW NR	ROTOR WARNINGS: HIGH NR	OTHER WARNINGS	COMMENTS
WESTLAND 30											
CWP				ENG <35PSI		EOP1 EOP2				DC ELEC – ELECTRICAL SUPPLY FAILURE	1ST FAILURE ONLY
AUDIO				T <35PSI							
				*							
WESTLAND S55											
CWP						ENG OIL P					
AUDIO										AUDIO (KLAXON) FOR ENGINE COMPUTER FAILURE	
						*					
WESSEX 60											
CWP	MASTER CAUTION					ENG P ENG S	FIRE P FIRE S			THR P THR S – ENGINE COMPUTER FAILURE	
AUDIO						T (THROUGH HEADSET)	T (THROUGH HEADSET)			T – MAIN GEARBOX LOW PRESSURE T – COUPLING GEARBOX LOW PRESSURE	

Table 4 Rotor RPM decay/power requirement comparison between HEL0602W and HAPS Westland 30 Models

Both models trimmed for level flight, weight = 12000 lb, cg. = aft, rotor rpm = 100% (326 rpm)

	Forward Airspeed	*HAPS model*	*HEL0602W model*
Total Power requirement	hover 40 knots 80 knots 120 knots	1600 shp 1100 shp 900 shp 1300 shp	1600 shp 900 shp 800 shp 1300 shp
Time to minimum continuous rotor rpm (92%) following an instantaneous total power loss	hover 40 knots 80 knots 120 knots	0·3 s 0·5 s 0·6 s 0·4 s	0·3 s 0·5 s 0·6 s 0·4 s
Time to minimum transient rotor rpm (76.7%) following an instantaneous total power loss	hover 40 knots 80 knots 120 knots	1·1 s 1·7 s 2·2 s 1·5 s	0·9 s 1·8 s 2·4 s 1·3 s

Table 5 Potential reduction in rotorcraft response time through the use of a Phase Advance Filter

Type of Total Power Loss	*Engine Torque Before Failure (%)*	*Time to Minimum continuous rotor rpm Warning (Seconds)*	*Phase Advanced 'Low Rotor' Warning (Seconds)*
Instantaneous	115 100 85 70 55 40	0·31 0·38 0·48 0·64 0·93 1·47	0·08 0·09 0·11 0·13 0·17 0·26
Gradual	115 100 85 70 55 40	0·83 0·94 1·10 1·30 1·63 2·20	0·33 0·37 0·43 0·50 0·61 0·80

Table 6 Variation in time to minimum transient rotor speed limit due to automatic intervention strategies (120 kts straight and level cruise)

INTERVENTION STRATEGY	*TIME TO MINIMUM TRANSIENT ROTOR SPEED LIMIT (SECONDS)*	
	Instantaneous Failure	*Gradual Failure*
None	1·7	2·4
Series actuator collective pitch reducer	2·0	2·85
Series actuator collective pitch reducer and ASE pitch input	4·8	>5
Slow full authority collective pusher	1·8	2·5
Fast full authority collective pusher	>5	>5

Table 7 Variation in time to minimum transient rotor speed limit due to automatic intervention strategies (hover)

INTERVENTION STRATEGY	*TIME TO MINIMUM TRANSIENT ROTOR SPEED LIMIT (SECONDS)*	
	Instantaneous Failure	*Gradual Failure*
None	1·05	1·8
Series actuator collective pitch reducer	1·24	2·15
Series actuator collective pitch reducer and ASE pitch input	1·24	2·15
Slow full authority collective pusher	1·07	1·88
Fast full authority collective pusher	2·0	>5

Table 8 Summary of Experimental Strategies

WARNING STRATEGY		*ENGINE FAILURE*		*FIRE*		*HYDRAULICS FAULT*		*PHASE ADVANCE FILTER*
		AUDIO	*VISUAL*	*AUDIO*	*VISUAL*	*AUDIO*	*VISUAL*	
1	BASELINE	LOW ROTOR RPM TONE ONLY	'ROTOR' CWP CAPTION	–	'FIRE' CWP CAPTION	–	'HYD' CWP CAPTION	NO
2	BASELINE + PREDICTION	LOW ROTOR RPM TONE ONLY	'ROTOR' CWP CAPTION	–	'FIRE' CWP CAPTION	–	'HYD' CWP CAPTION	YES
3	MULTITONES	HI/LO ROTOR RPM TONES	'ROTOR' CWP CAPTION	FIRE TONE	'FIRE' CWP CAPTION	HYD TONE	'HYD' CWP CAPTION	YES
4	ENHANCED VISUAL	HI/LO ROTOR RPM TONES	'ROTOR' CWP CAPTION + DEDICATED ATTENTION GETTERS	FIRE TONE	'FIRE' CWP CAPTION	HYD TONE	'HYD' CWP CAPTION	YES
5	TONES + MESSAGE	HI/LO ROTOR RPM TONES + MESSAGE	'ROTOR' CWP CAPTION	FIRE TONE + MESSAGE	'FIRE' CWP CAPTION	HYD TONE + MESSAGE	'HYD' CWP CAPTION	YES
6	MODULATED TONE	MODULATED ROTOR RPM TONE	'ROTOR' CWP CAPTION	FIRE TONE	'FIRE' CWP CAPTION	HYD TONE	'HYD' CWP CAPTION	YES
7	AUTOMATED INTERVENTION 1	HI/LO ROTOR RPM TONE	'ROTOR' CWP CAPTION	FIRE TONE	'FIRE' CWP CAPTION	HYD TONE	'HYD' CWP CAPTION	YES
8	AUTOMATED INTERVENTION 2	HI/LO ROTOR RPM TONE	'ROTOR' CWP CAPTION	FIRE TONE	'FIRE' CWP CAPTION	HYD TONE	'HYD' CWP CAPTION	YES

Table 9 Quantitative Results Summary

	STRATEGY							
ATTENTIVE FLIGHT	*BASELINE*	*BASELINE + PREDICTION*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
Mean Rotorcraft Response Time (Secs)	1·50	0·58	0·56	0·57	0·56	0·57	0·57	0·57
Standard deviation	0·15	0·01	0·02	0·01	0·01	0·01	0·02	0·01
Mean Pilot Response Time (Secs)	0·08	0·52	0·72	0·62	0·61	0·61	0·63	0·51
Standard deviation	0·64	0·33	0·44	0·35	0·27	0·35	0·32	0·06
Mean Actual Intervention Time (Secs)	1·58	1·10	1·29	1·19	1·18	1·18	1·20	1·08
Standard deviation	0·57	0·32	0·44	0·36	0·28	0·37	0·32	0·06
Mean Available Intervention Time (Secs)	2·11	2·11	2·11	2·11	2·11	2·11	30·80	1000·00
Standard deviation	0·16	0·16	0·16	0·16	0·16	0·16	0·00	0·00
Mean Time to Min Collective (Secs)	0·90	0·94	0·91	0·88	1·00	1·10	1·12	0·86
Standard deviation	0·48	0·51	0·44	0·49	0·55	0·64	0·66	0·37
Mean Min Nr Value (%)	81·97	86·42	84·30	86·15	85·45	85·23	89·45	86·68
Standard deviation	4·08	3·44	4·27	3·57	3·50	3·44	1·31	0·78

	STRATEGY							
PASSIVE FLIGHT	*BASELINE*	*BASELINE + PREDICTION*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
Mean Rotorcraft Response Time (Secs)	1·24	0·48	0·50	0·49	0·49	0·49	0·49	0·49
Standard deviation	0·07	0·01	0·01	0·01	0·01	0·02	0·02	0·02
Mean Pilot Response Time (Secs)	0·70	1·31	1·36	1·34	1·43	1·42	1·46	0·37
Standard deviation	0·55	0·41	0·43	0·40	0·39	0·38	0·67	0·02
Mean Actual Intervention Time (Secs)	1·94	1·79	1·86	1·84	1·92	1·90	1·96	0·86
Standard deviation	0·52	0·41	0·43	0·39	0·39	0·39	0·68	0·03
Mean Available Intervention Time (Secs)	1·59	1·59	1·59	1·59	1·59	1·59	5·40	1000·00
Standard deviation	0·12	0·12	0·12	0·12	0·12	0·12	0·00	0·00
Mean Time to Min Collective (Secs)	1·19	0·82	0·80	0·82	0·79	0·66	1·15	0·79
Standard deviation	1·28	0·41	0·58	0·52	0·43	0·19	0·74	0·48
Mean Min Nr Value (%)	72·40	73·69	73·50	73·93	71·96	73·14	85·15	82·69
Standard deviation	4·71	4·71	4·28	3·78	3·37	3·66	1·72	0·74

Table 10 Analysis of Variance Summary Table
Actual Intervention Time Data

SOURCE	*df*	*SS*	*MS*	*F*	*Sig*
Attention level	1	14·852	14·852	147·308 $_{(1,12)}$	p <0·001
Strategy	7	9·490	1·355	14·228 $_{(7,84)}$	p <0·001
Subjects	12	16·532	1·377	21·378 $_{(12,84)}$	p <0·001
Attention level x Strategy	7	5·029	0·718	11·095 $_{(7,84)}$	p <0·001
Attention level x Subjects	12	1·209	0·100		
Strategy x Subjects	84	8·004	0·095		
Attention x Strategy x Subjects	84	5·438	0·064		
Total	207	60·558			

Definitions

df = Degrees of freedom
SS = Sum of squares
MS = Mean square
F = F Statistic
Sig = Level of significance

Table 11 Dunn's Test on Actual Intervention Time for Attentive Flight

SOURCE	*df*	*SS*	*MS*	*F*
Strategies	7	2·25	0·32	2·41
Error	96	12·73	0·132	
Total	103	14·98		

C = 7 (number of comparisons)
$\alpha = 0{\cdot}01$
dferror = 96 (For a conservative estimate, assume df = 75)
therefore
$t^{l} = 3{\cdot}31$

Critical Difference (i.e. smallest difference in totals which leads to rejection of the null hypothesis (Ho) at $\alpha = 0{\cdot}01$)

$= t^{l}\ \sqrt{2n\ MSerror}$

$= 3{\cdot}31\ \sqrt{2 \times 13 \times 0{\cdot}132} = 6{\cdot}13\ secs$

	COMPARISONS	*TOTALS*	*DIFFERENCE*
1	Baseline v Baseline + Prediction	20·54 – 14·26 =	6·28*
2	Baseline + Prediction v Multitones	14·26 – 16·76 =	–2.5
3	Multitones v Enhanced Visual	16·76 – 15·44 =	1·32
4	Multitones v Tones + Message	16·76 – 15·32 =	1·44
5	Multitones v Mod Tone	16·76 – 15·32 =	1·44
6	Multitones v Auto 1	16·76 – 15·56 =	1·2
7	Multitones v Auto 2	16·76 – 14·08 =	2·68

* Significant (p <0·01)

Table 12 Dunn's Test on Actual Intervention Time for Passive Flight

SOURCE	*df*	*SS*	*MS*	*F*
Strategies	7	12·27	1·75	9·21
Error	96	18·43	0·19	
Total	103	30·71		

C = 7 (number of comparisons)
$\alpha = 0{\cdot}01$
dferror = 96 (For a conservative estimate assume df = 75)
therefore
$t^{l} = 3{\cdot}31$

Critical Difference (i.e. smallest difference in totals which leads to rejection of the null hypothesis (Ho) at $\alpha = 0.01$)

$= t^{l} \sqrt{2n\ MSerror}$

$= 3{\cdot}31 \sqrt{2 \times 13 \times 0{\cdot}19} = 7{\cdot}35$ *secs*

	COMPARISONS	*TOTALS*	*DIFFERENCE*
1	Baseline v Baseline + Prediction	25·22 – 23·28 =	1·94
2	Baseline + Prediction v Multitones	23·28 – 24·18 =	–0·9
3	Multitones v Enhanced Visual	24·18 – 23·86 =	0·32
4	Multitones v Tones + Message	24·18 – 24·96 =	–0·78
5	Multitones v Mod Tone	24·18 – 24·76 =	–0·58
6	Multitones v Auto 1	24·18 – 25·42 =	–1·24
7	Multitones v Auto 2	24·18 – 11·18 =	13·00*

* Significant (p <0·01)

Table 13 Analysis of Variance Summary Table
Minimum Nr Data

SOURCE	*df*	*SS*	*MS*	*F*	*Sig*
Attention level	1	5094·342	5094·342	$772{\cdot}198_{(1,12)}$	$p<0{\cdot}001$
Strategy	7	2136·105	305·158	$39{\cdot}454_{(7,84)}$	$p<0{\cdot}001$
Subjects	12	1212·751	101·062	$24{\cdot}130_{(12,84)}$	$p<0{\cdot}001$
Attention level x Strategy	7	639·147	91·306	$21{\cdot}801_{(7,84)}$	$p<0{\cdot}001$
Attention level x Subjects	12	79·166	6·597		
Strategy x Subjects	84	649·687	7·734		
Attention x Strategy x Subjects	84	351·804	4·188		
Total	207	10163			

Definitions

df = Degrees of freedom
SS = Sum of squares
MS = Mean square
F = F Statistic
Sig = Level of significance

Table 14 Dunn's Test on Minimum Value of Nr achieved for Attentive Flight

SOURCE	*df*	*SS*	*MS*	*F*
Strategies	7	414·53	59·22	5·51
Error	96	1030·65	10·74	
Total	103	1445·18		

C = 7 (number of comparisons)
$\alpha = 0{\cdot}01$
dferror = 96 (For a more conservative estimate assume df = 75)
therefore
$t^{I} = 3{\cdot}31$

Critical Difference (i.e. smallest difference in totals which leads to rejection of the null hypothesis (Ho) at $\alpha = 0{\cdot}01$)

$$= t^{I} \sqrt{2n\ MSerror}$$

$$= 3{\cdot}31 \sqrt{2 \times 13 \times 10{\cdot}74} = 55{\cdot}31\%$$

	COMPARISONS	*TOTALS*	*DIFFERENCE*
1	Baseline v Baseline + Prediction	1065·63 – 1123·51 =	–57·88*
2	Baseline + Prediction v Multitones	1123·51 – 1095·92 =	27·59
3	Multitones v Enhanced Visual	1095·92 – 1119·89 =	–23·97
4	Multitones v Tones + Message	1095·92 – 1110·79 =	–14·87
5	Multitones v Mod Tone	1095·92 – 1107·96 =	–12·04
6	Multitones v Auto 1	1095·92 – 1162·86 =	–66·94*
7	Multitones v Auto 2	1095·92 – 1126·78 =	–30·86

* Significant ($p < 0{\cdot}01$)

Table 15 Dunn's Test on Minimum Value of Nr achieved for Passive Flight

SOURCE	*df*	*SS*	*MS*	*F*
Strategies	7	2340·29	334·33	25·00
Error	96	1283·13	13·37	
Total	103	3623·42		

C = 7 (number of comparisons)
$\alpha = 0{\cdot}01$
dferror = 96 (For a more conservative estimate assume df = 75)
therefore
$t^{l} = 3{\cdot}31$

Critical Difference (i.e. smallest difference in totals which leads to rejection of the null hypothesis (Ho) at $\alpha = 0{\cdot}01$)

$= t^{l}\ \sqrt{2n\ MSerror}$

$= 3{\cdot}31\ \sqrt{2 \times 13 \times 13{\cdot}37} = 61{\cdot}71\%$

	COMPARISONS	*TOTALS*	*DIFFERENCE*
1	Baseline v Baseline + Prediction	941·17 – 957·92 =	–16·75
2	Baseline + Prediction v Multitones	957·92 – 955·45 =	2·47
3	Multitones v Enhanced Visual	955·45 – 961·07 =	–5·62
4	Multitones v Tones + Message	955·45 – 935·52 =	19·93
5	Multitones v Mod Tone	955·45 – 950·86 =	4·59
6	Multitones v Auto 1	955·45 – 1106·98 =	–151·53*
7	Multitones v Auto 2	955·45 – 1074·99 =	–119·54*

* Significant at ($p < 0{\cdot}01$)

Table 16 Summary of Relative Strategy Performance

STRATEGY	*ATTENTIVE FLIGHT*		*PASSIVE FLIGHT*	
	*Qualitative View**	*Subjective View Median*	*Qualitative View**	*Subjective View Median*
BASELINE	GOOD	4	POOR	4
BASELINE + PREDICTION	GOOD	5	POOR	5
MULTITONES	FAIR	4	POOR	5
ENHANCED VISUAL	GOOD	5	POOR	5
TONES + MESSAGE	GOOD	5	POOR	5
MODULATED TONE	GOOD	5	POOR	5
AUTO 1	GOOD	5	GOOD	6
AUTO 2	GOOD	6	GOOD	6

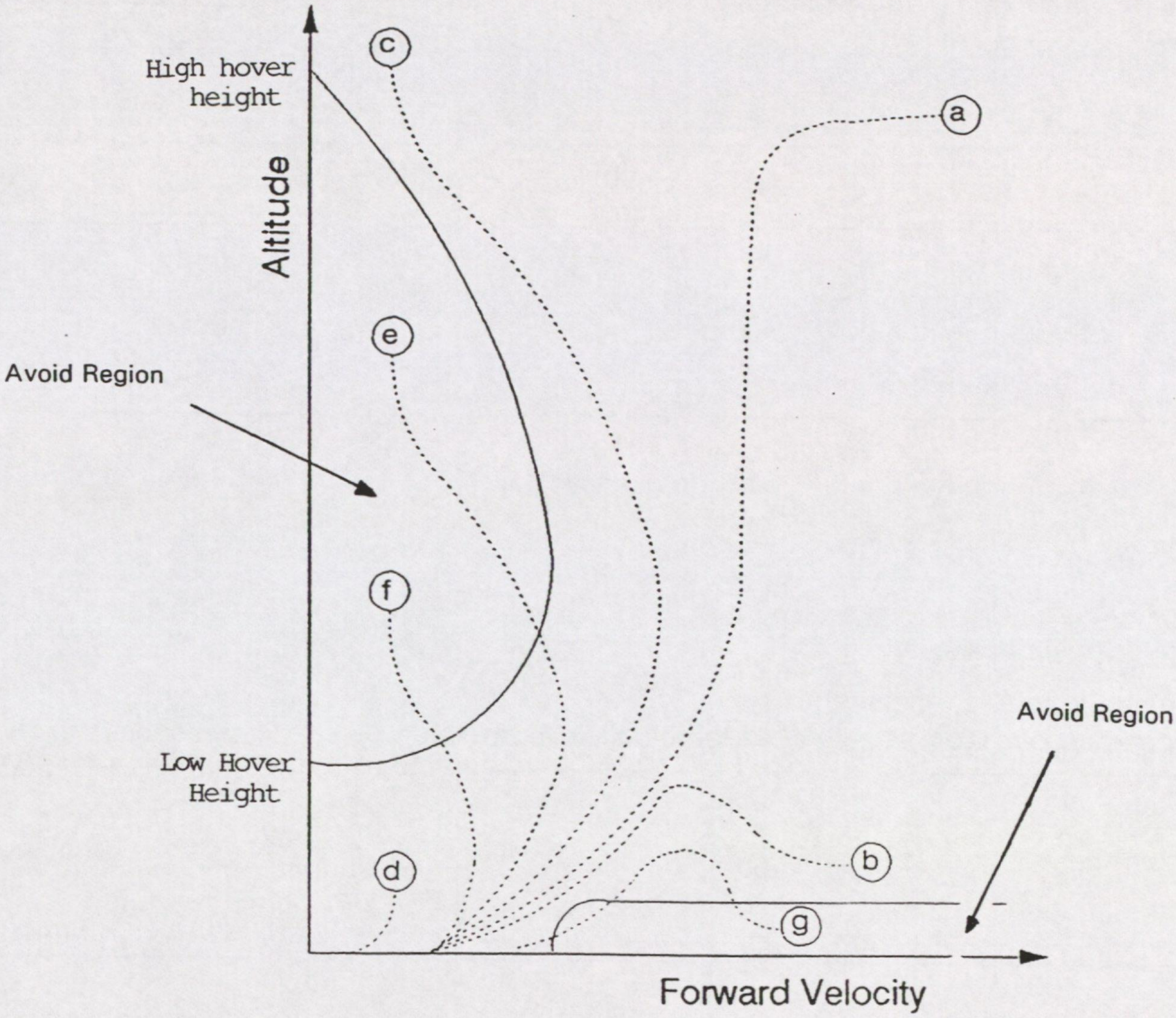
* – Defined as:

GOOD – Minimum Nr values from all subjects are above the minimum Nr transient limit.

FAIR – The mean minimum Nr reached from all subjects is above the minimum transient limit, although the range of minimum Nr values transgresses the limit.

POOR – The mean minimum Nr from all subjects is below the minimum Nr transient limit.

Figures



a	IFEC:	Lower collective rapidly (and pitch nose up if above min power speed)
	PILOT:	Enter autorotational descent cushion landing with collective
b	IFEC:	Flare, controlling rotor speed with collective
	PILOT:	Cushion landing with collective
c	IFEC:	Lower collective rapidly and pitch aircraft down
	PILOT:	Autorotational descent, flare and cushion landing with collective
d	IFEC:	Ensure collective is raised to cushion landing
	PILOT:	Cushion landing with collective
e	IFEC:	Lower collective rapidly and pitch aircraft down (ensure collective is raised to cushion landing)
	PILOT:	Cushion landing with collective
f	IFEC:	Lower collective rapidly and cushion landing with collective
g	IFEC:	Increase collective slightly to clear ground, then flare
	PILOT:	Cushion landing with collective

Figure 1 Schematic avoid curve showing action of both pilot and Integrated Flight & Engine Control (IFEC) system in the event of a total power loss

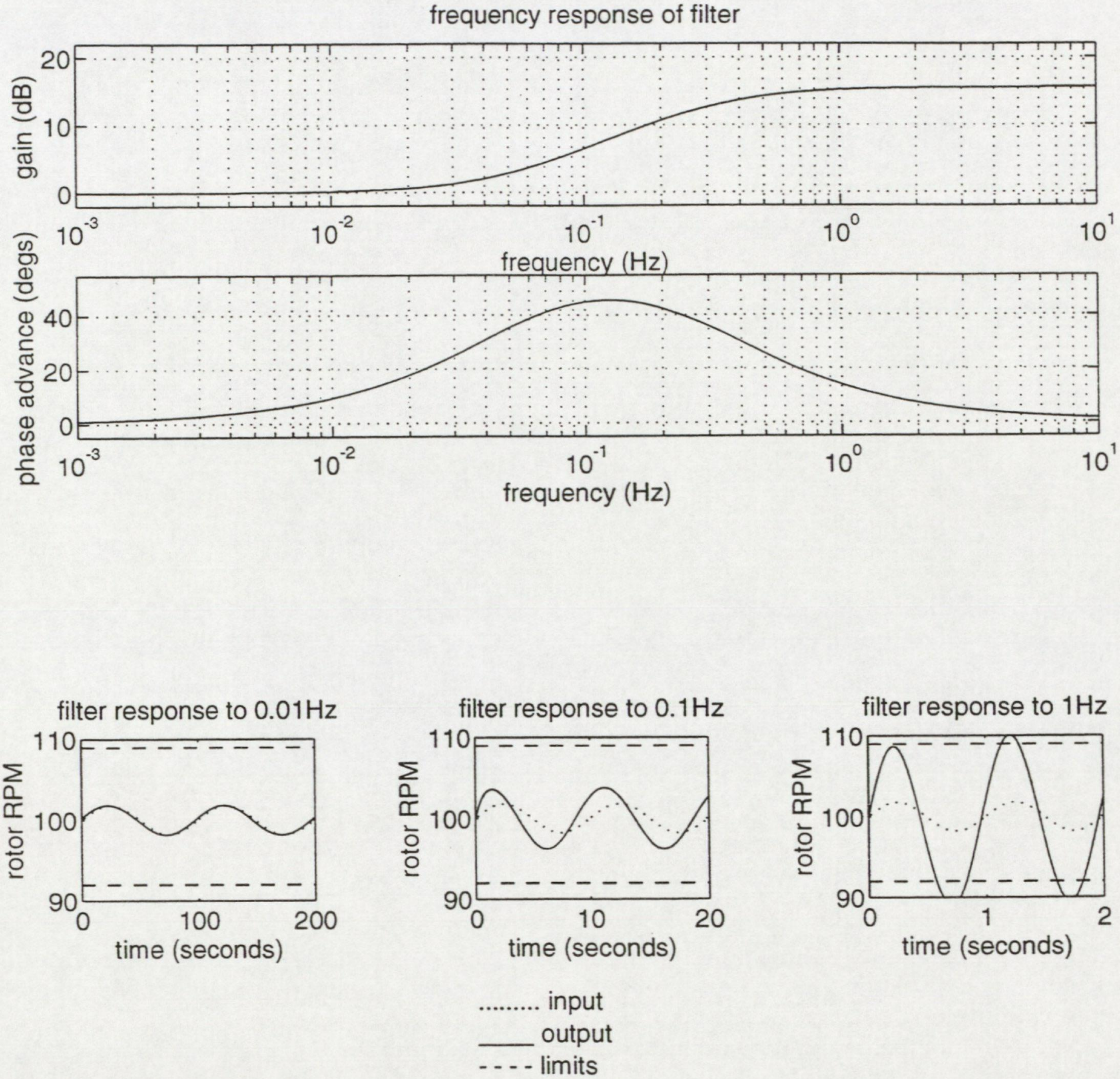


Figure 1A Frequency and Time Domain Characteristics for the Rotor rpm Prediction Filter: $G(s) = (1+3.145*s)/(1+0{\cdot}524*s)$

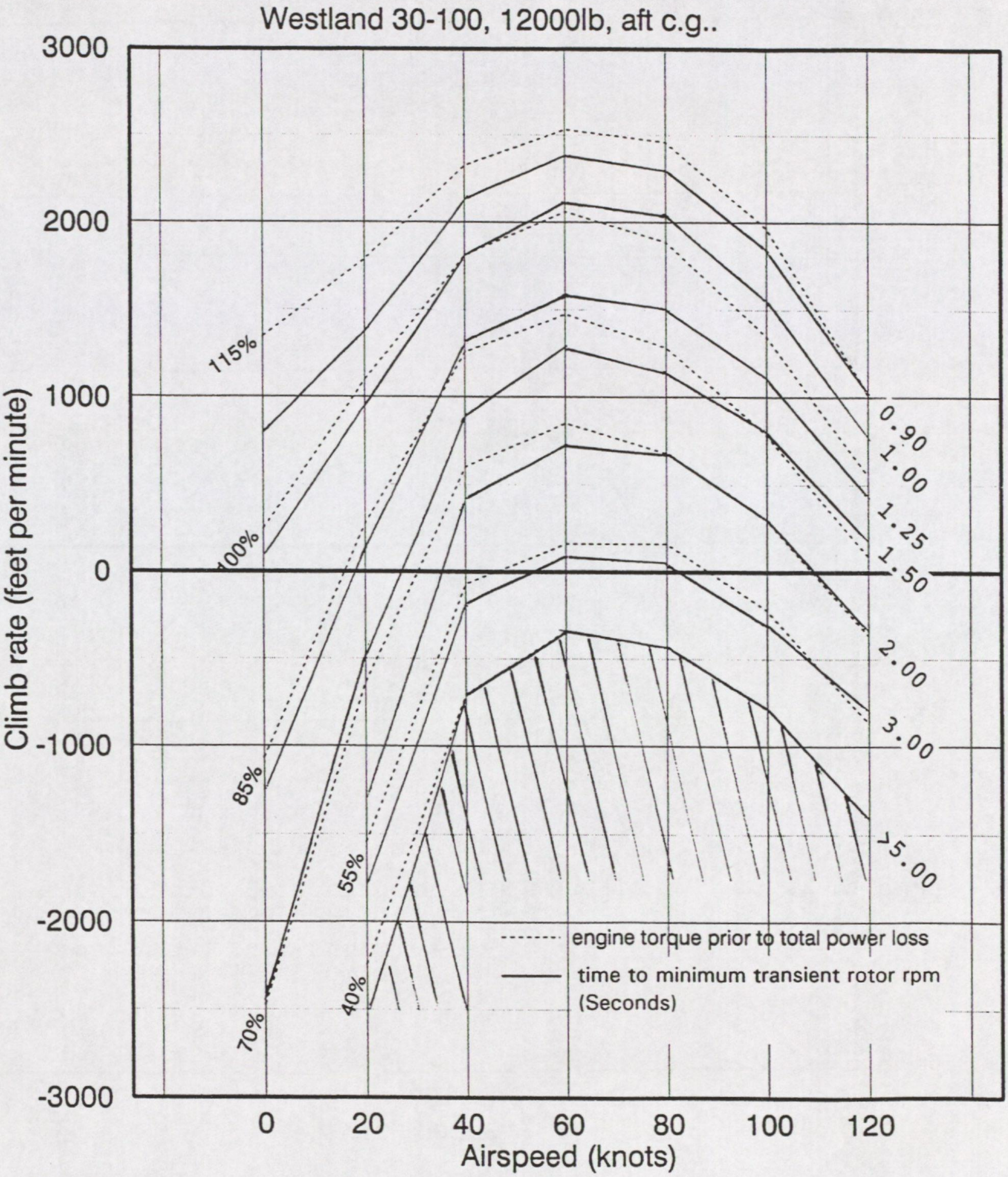


Figure 2 Time to Minimum Transient Rotor Speed. Instantaneous Total Power Loss Scenario

Intervention Strategy: None (Controls Fixed)

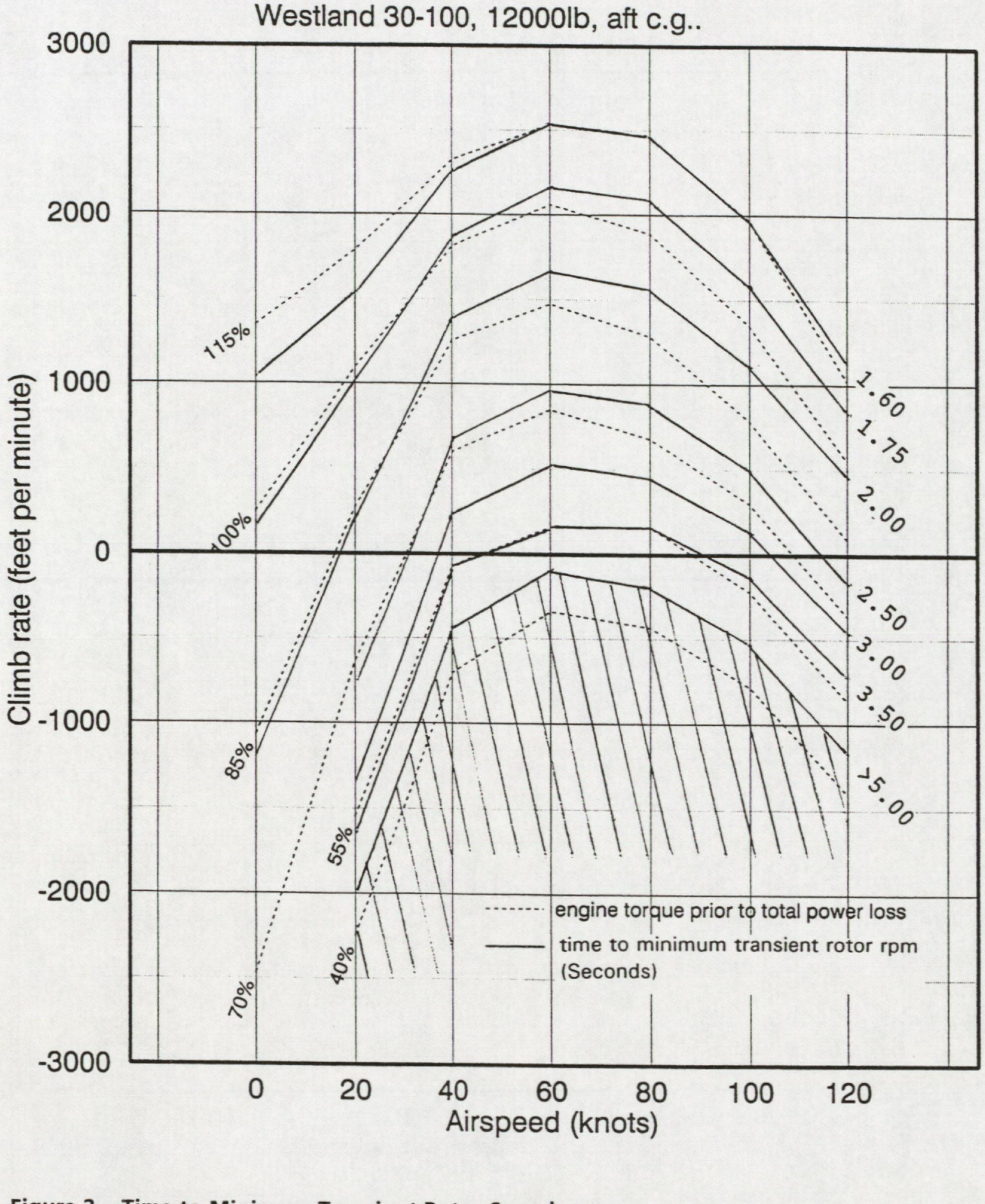


Figure 3 Time to Minimum Transient Rotor Speed. Gradual Total Power Loss Scenario

Intervention Strategy: None (Controls Fixed)

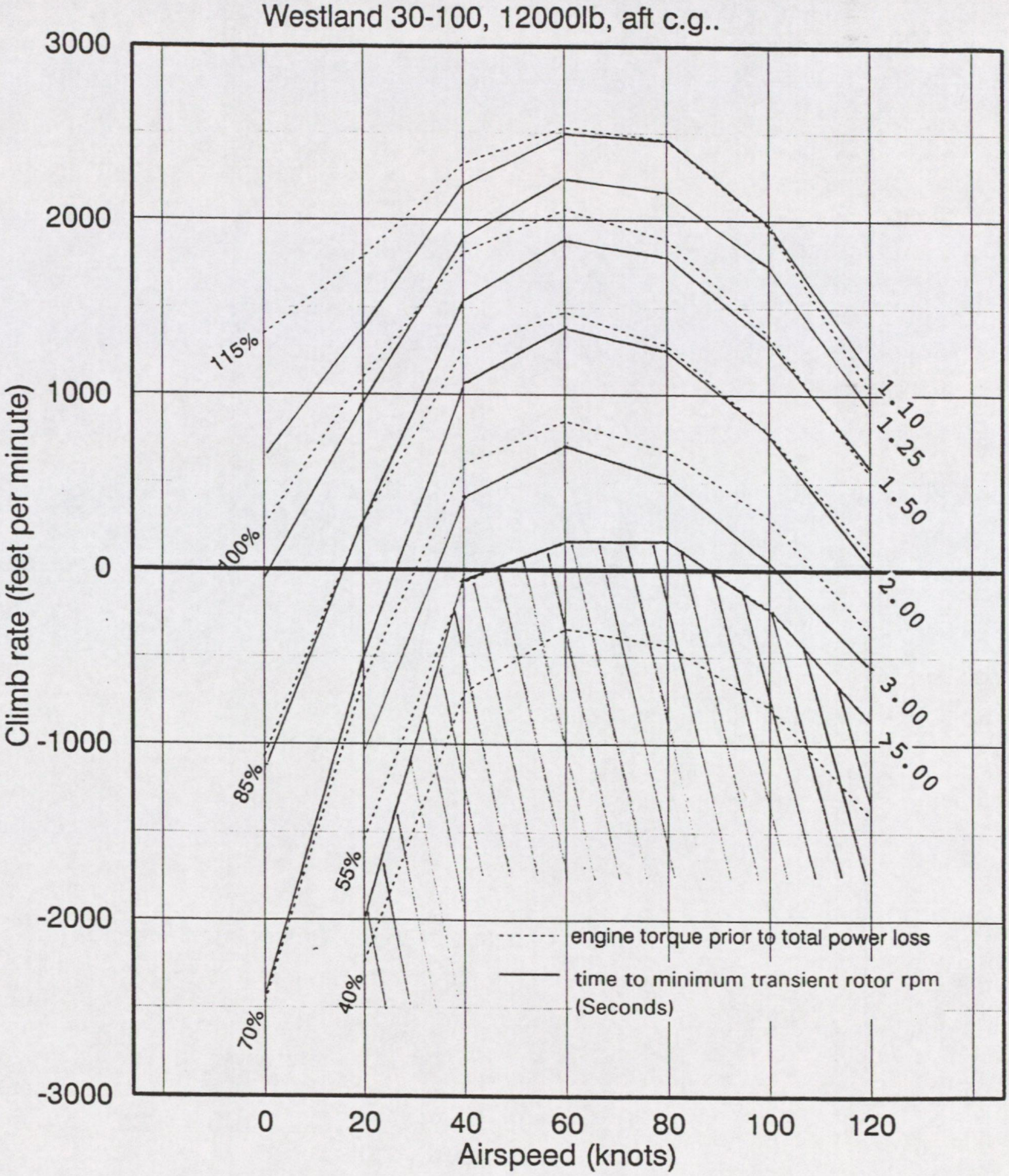


Figure 4 Time to Minimum Transient Rotor Speed. Instantaneous Total Power Loss Scenario

Intervention Strategy: 10% Collective pitch reduction (via a series actuator)

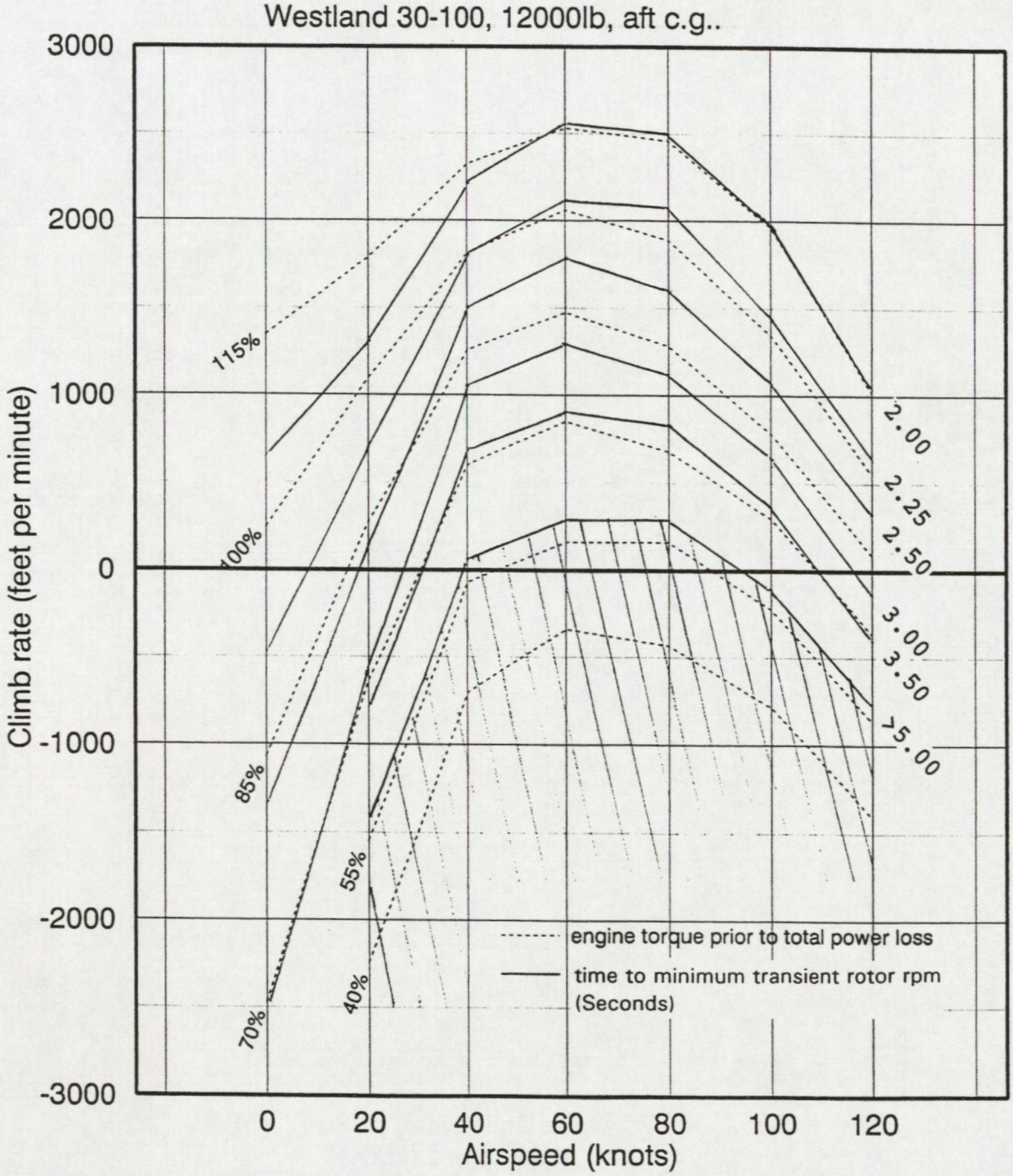


Figure 5 Time to Minimum Transient Rotor Speed. Gradual Total Power Loss Scenario

Intervention Strategy: 10% Collective pitch reduction (via a series actuator)

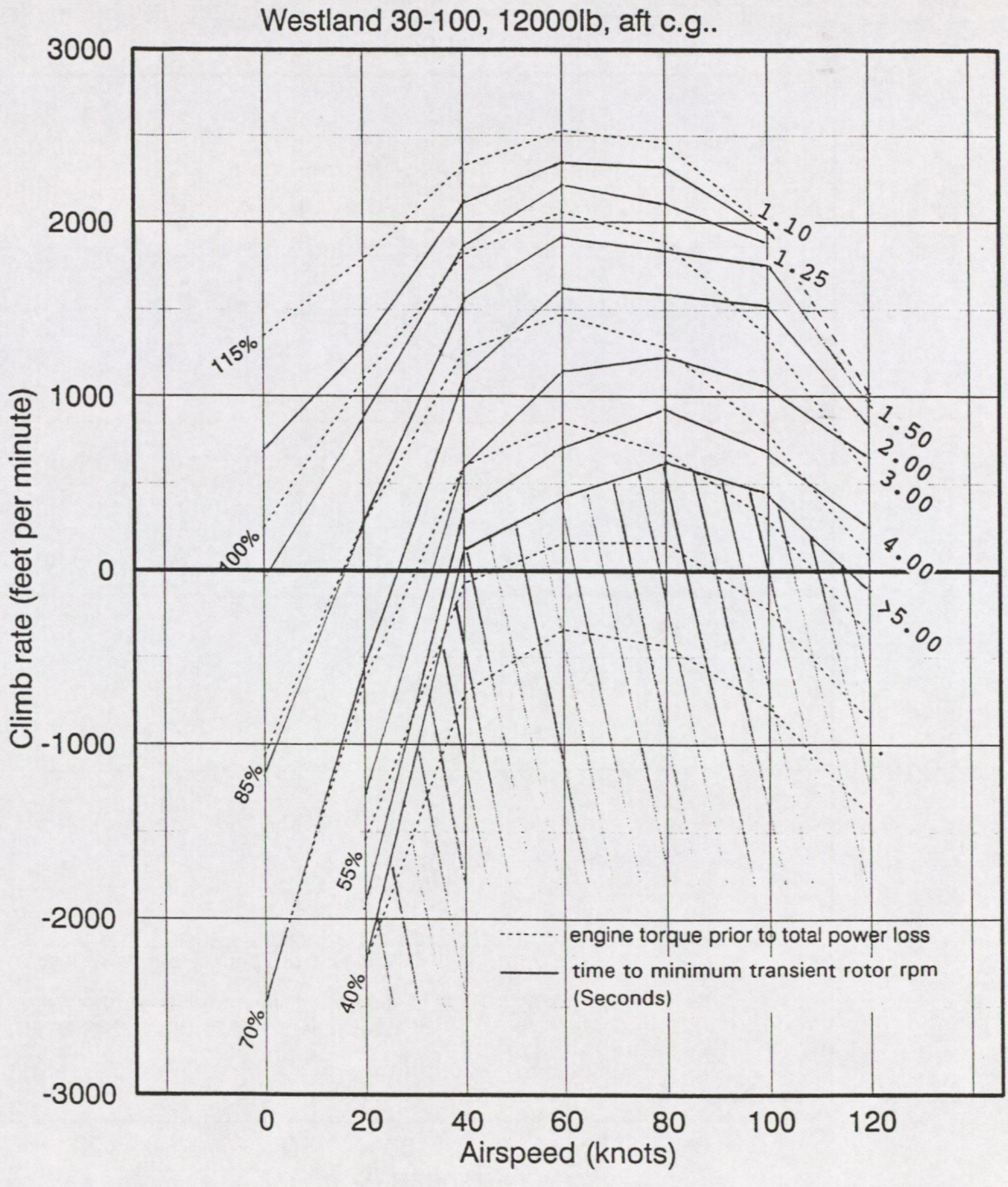


Figure 6 Time to Minimum Transient Rotor Speed. Instantaneous Total Power Loss Scenario

Intervention Strategy: 10% Collective pitch reduction and 10 degree flare (via ASE)

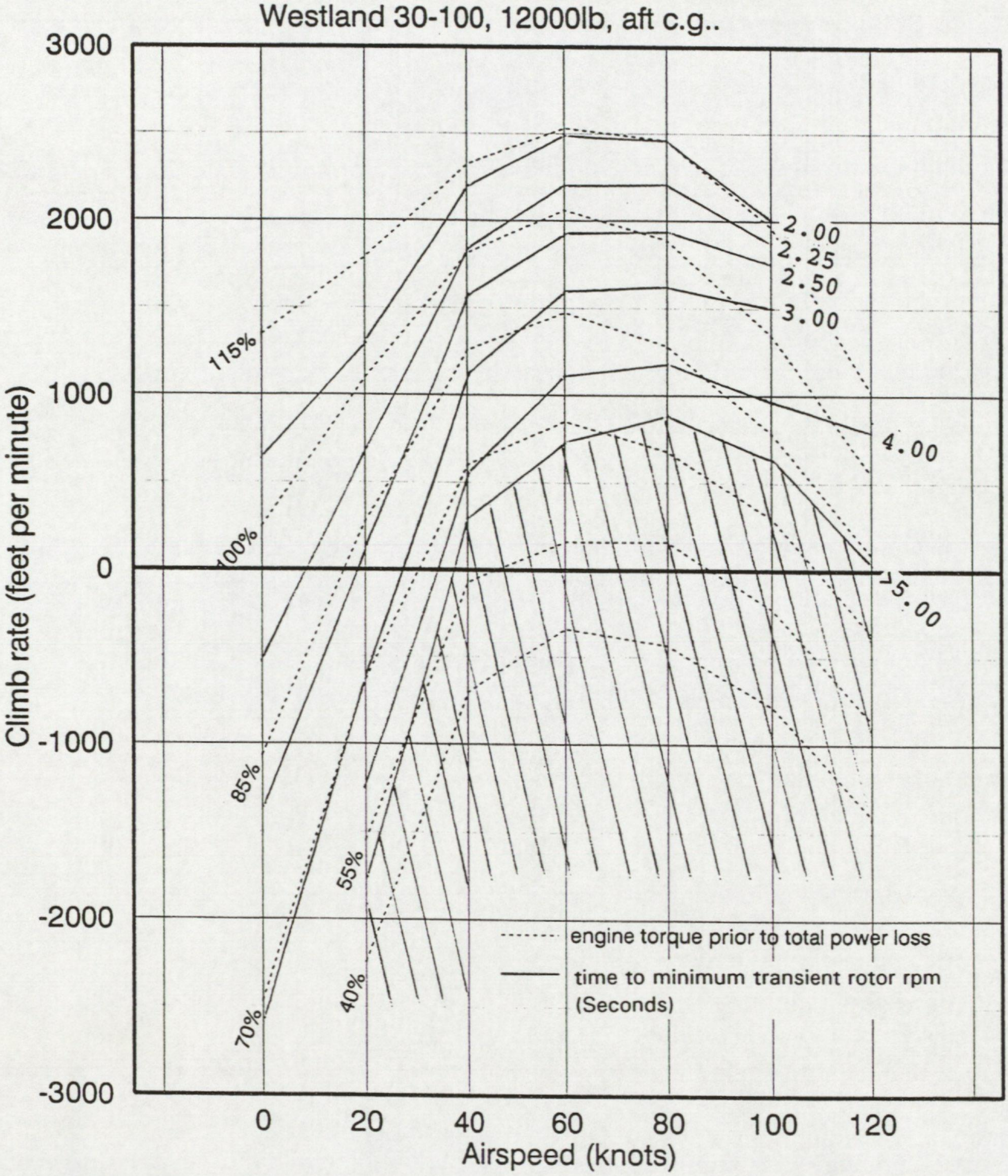


Figure 7 Time to Minimum Transient Rotor Speed. Gradual Total Power Loss Scenario

Intervention Strategy: 10% Collective pitch reduction and 10 degree flare (via ASE)

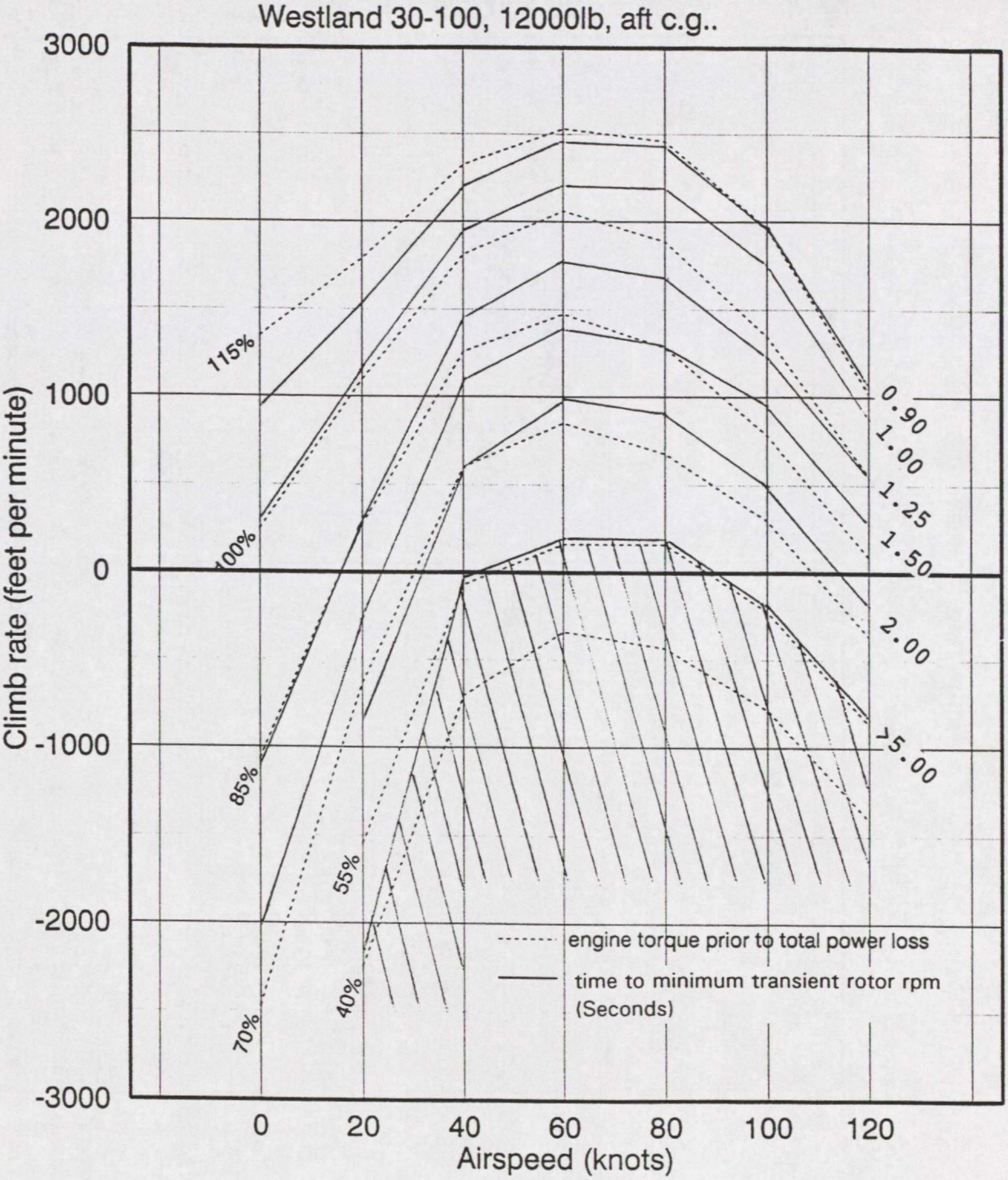


Figure 8 Time to Minimum Transient Rotor Speed. Instantaneous Total Power Loss Scenario

Intervention Strategy: Slow collective lowering system (via a parallel actuator)

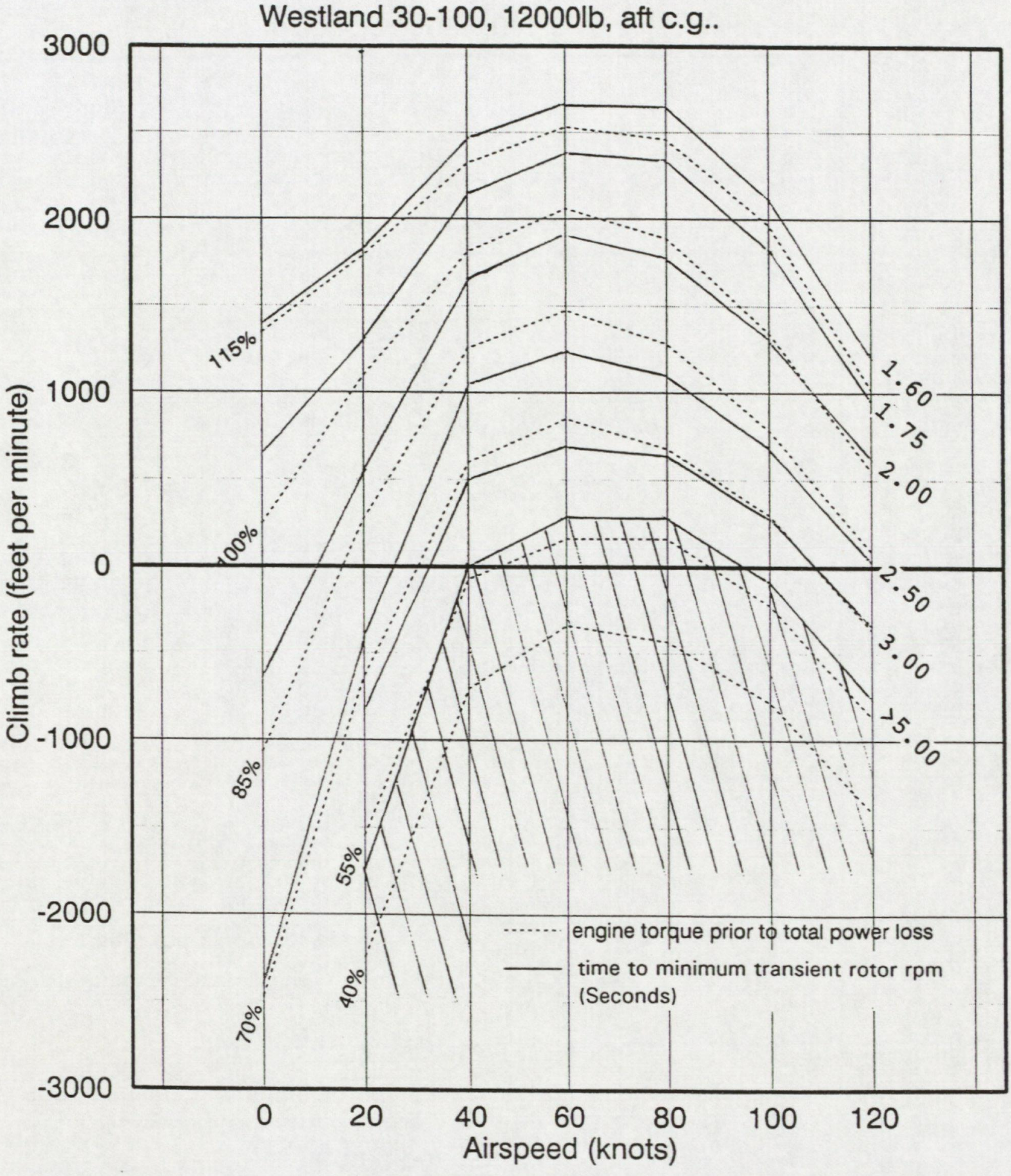


Figure 9 Time to Minimum Transient Rotor Speed. Gradual Total Power Loss Scenario

Intervention Strategy: Slow collective lowering system (via a parallel actuator)

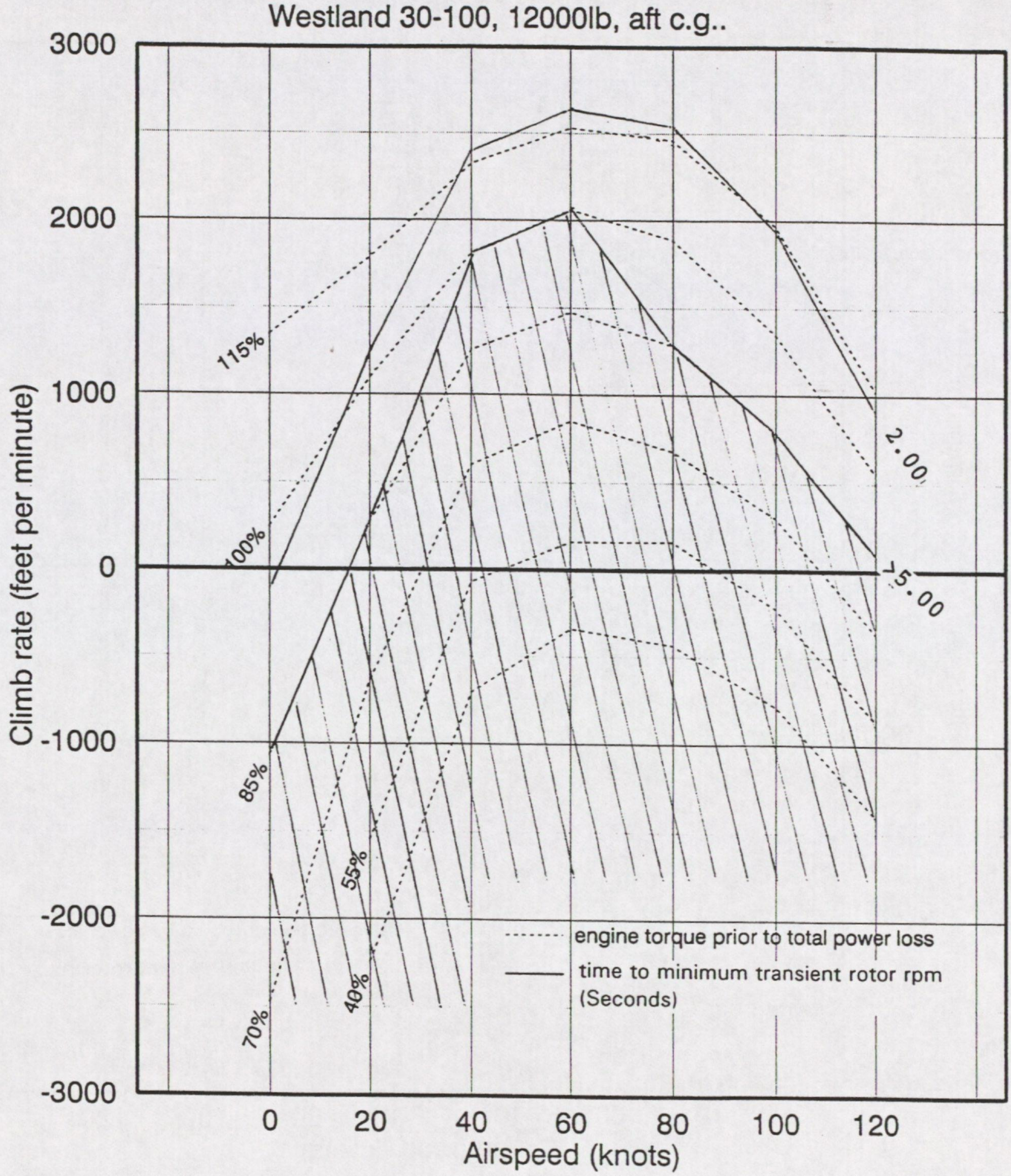


Figure 10 Time to Minimum Transient Rotor Speed.
Instantaneous Total Power Loss Scenario

Intervention Strategy: Fast collective lowering system (2 seconds stop-to-stop)

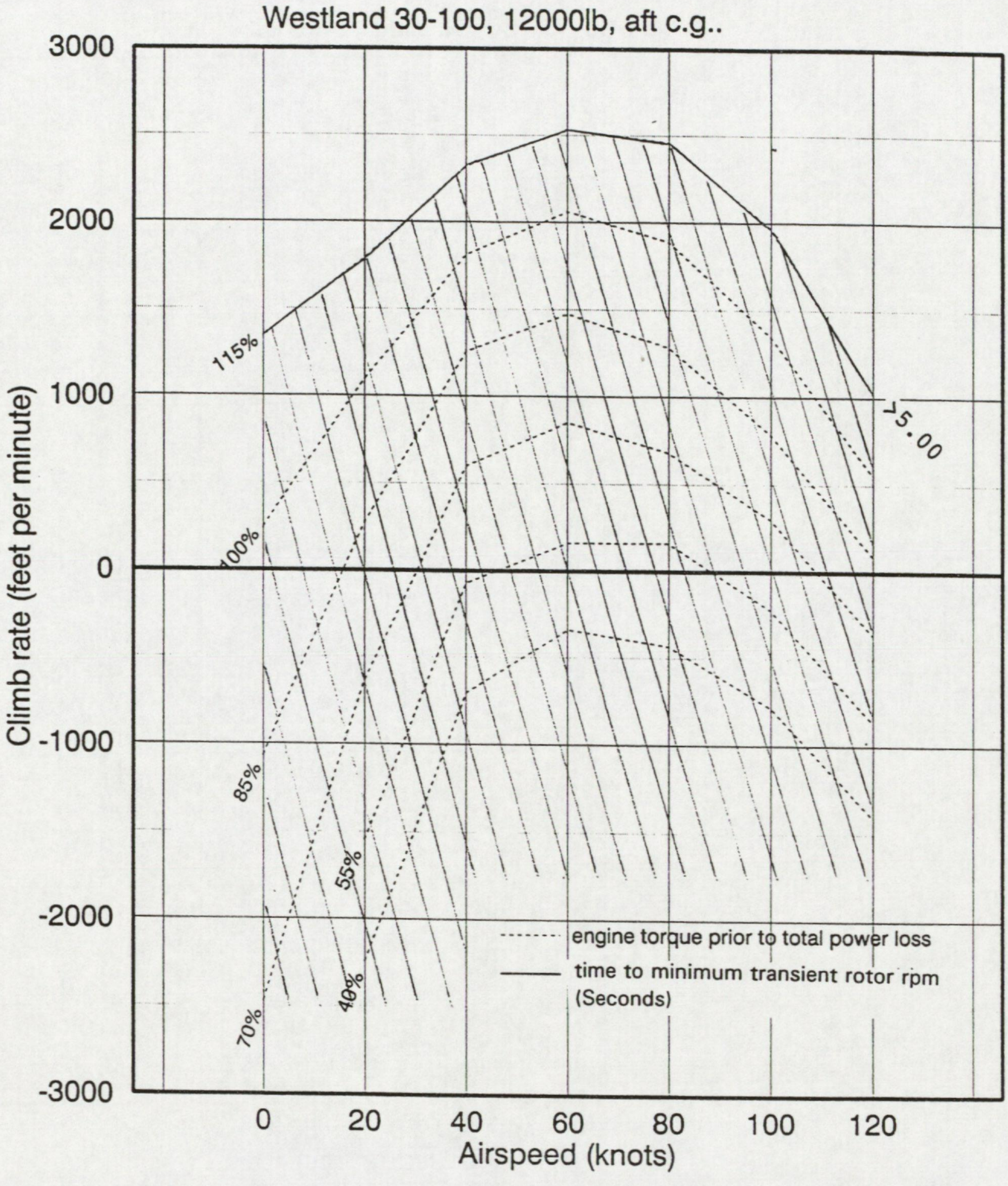


Figure 11 Time to Minimum Transient Rotor Speed.
Gradual Total Power Loss Scenario

Intervention Strategy: Fast collective lowering system (2 seconds stop-to-stop)

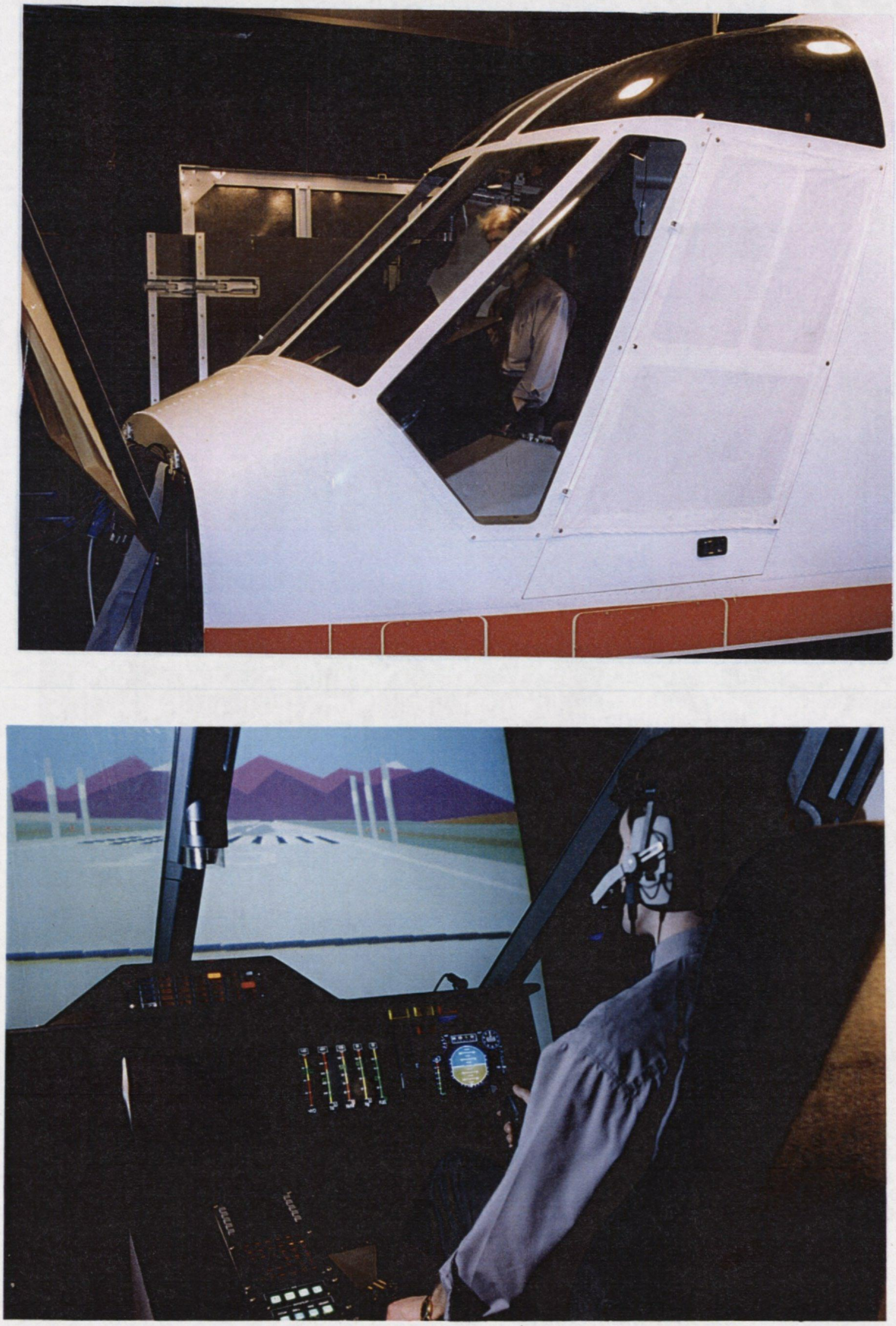


Figure 12 The WHL Advanced Engineering Simulator Facility

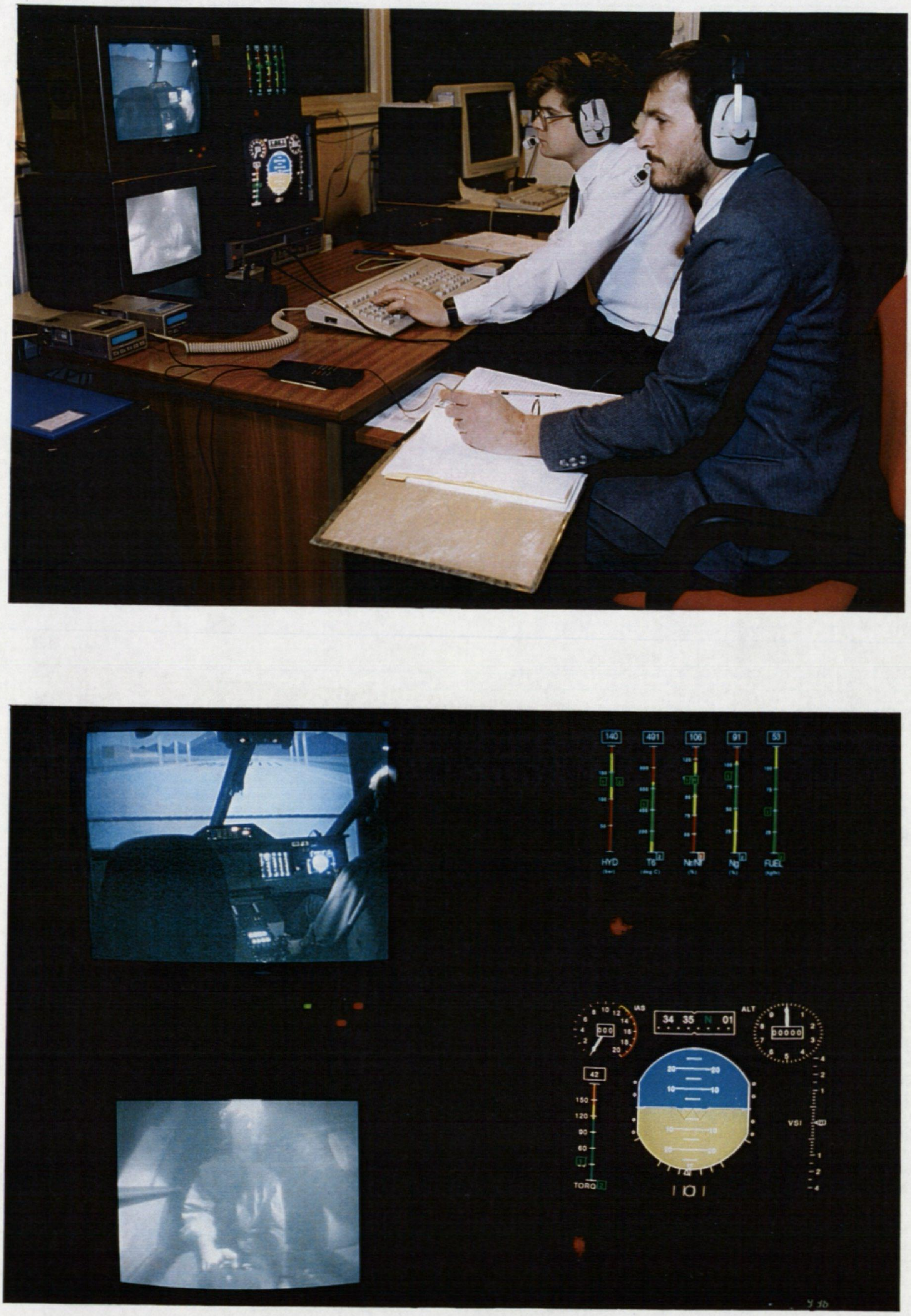


Figure 13 The Simulator Control Room and Monitoring Equipment

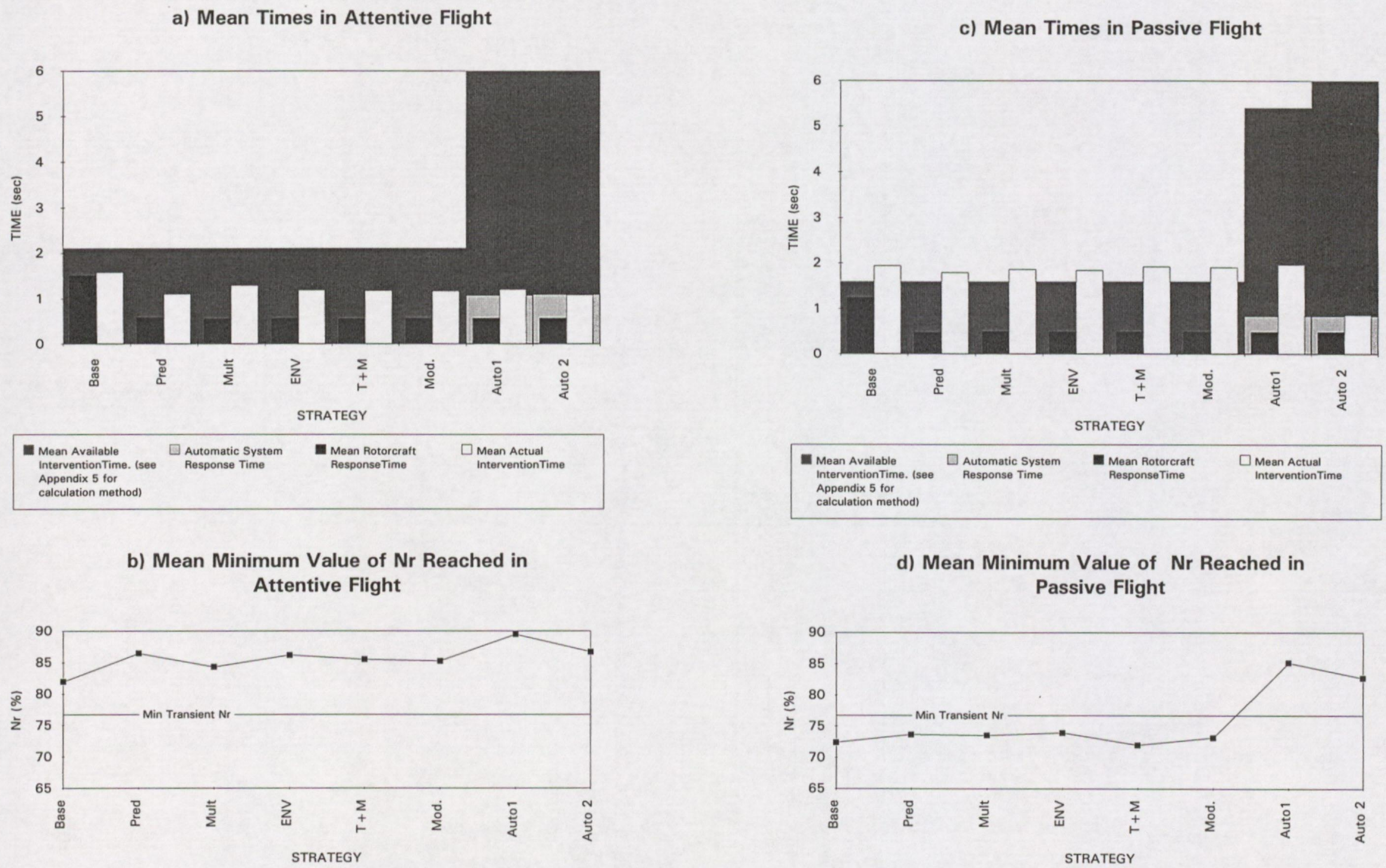


Figure 14 Mean Pilot and System Response Times for Each Strategy

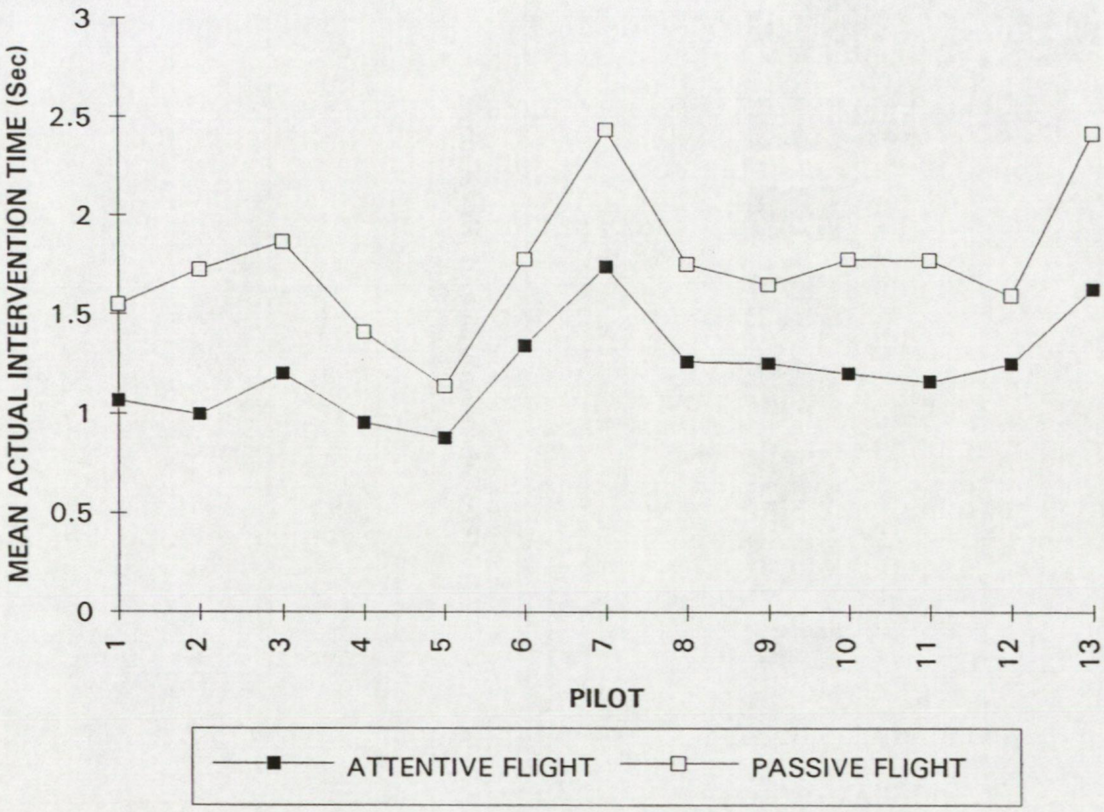


Figure 15 Mean Actual Intervention Times by Pilots

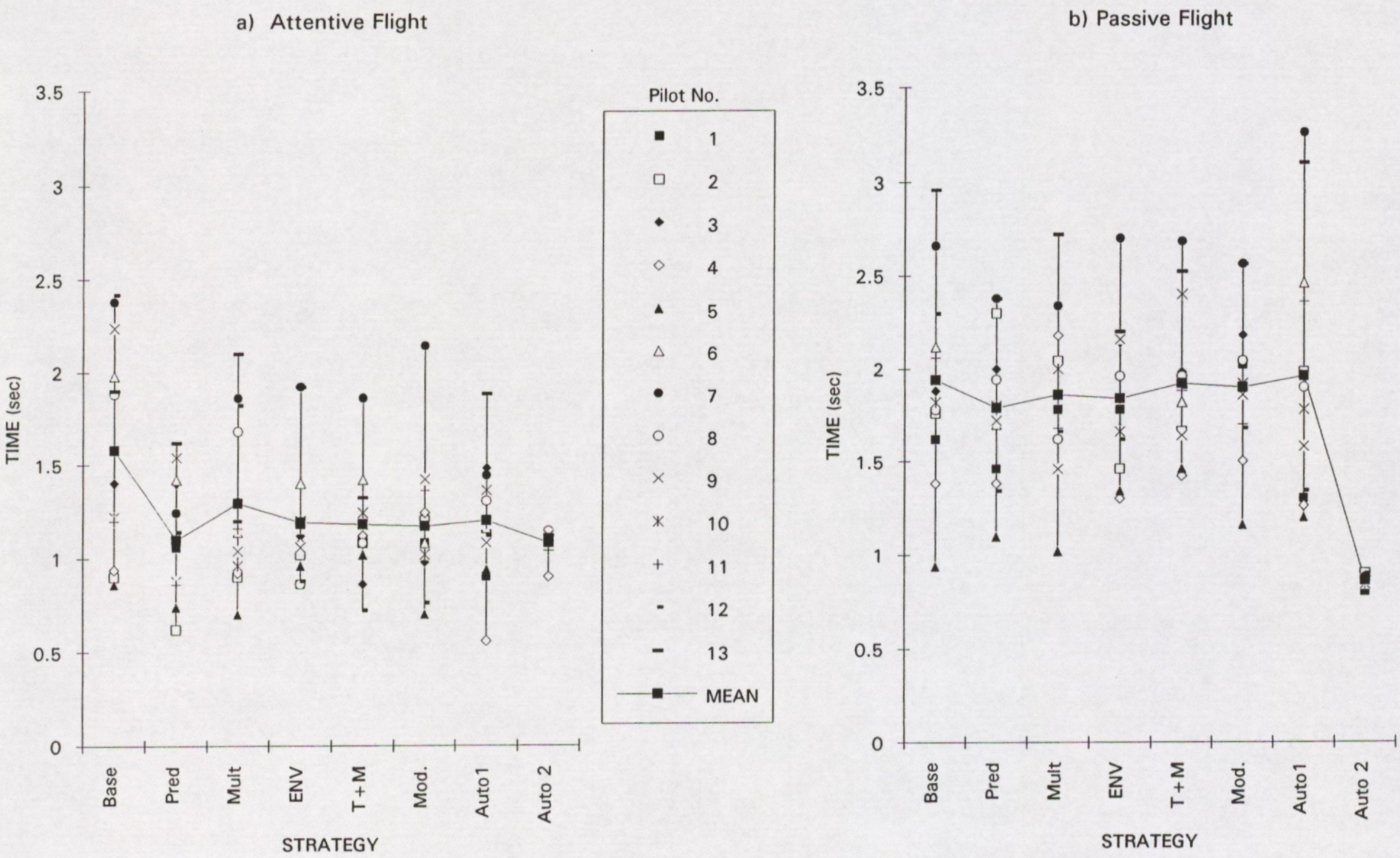


Figure 16 Distribution of Actual Intervention Times

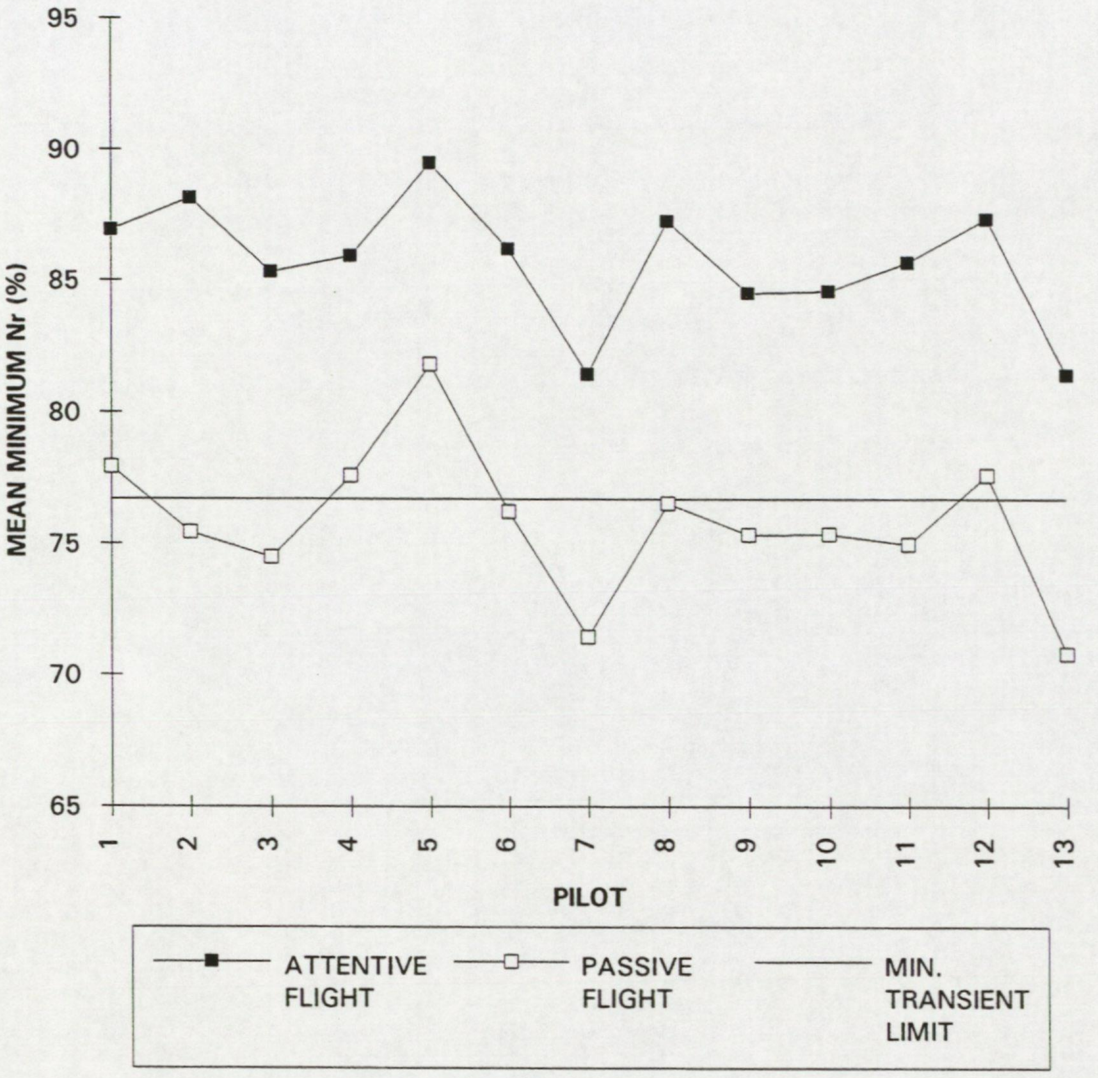


Figure 17 Mean Minimum Nr Values by Pilot

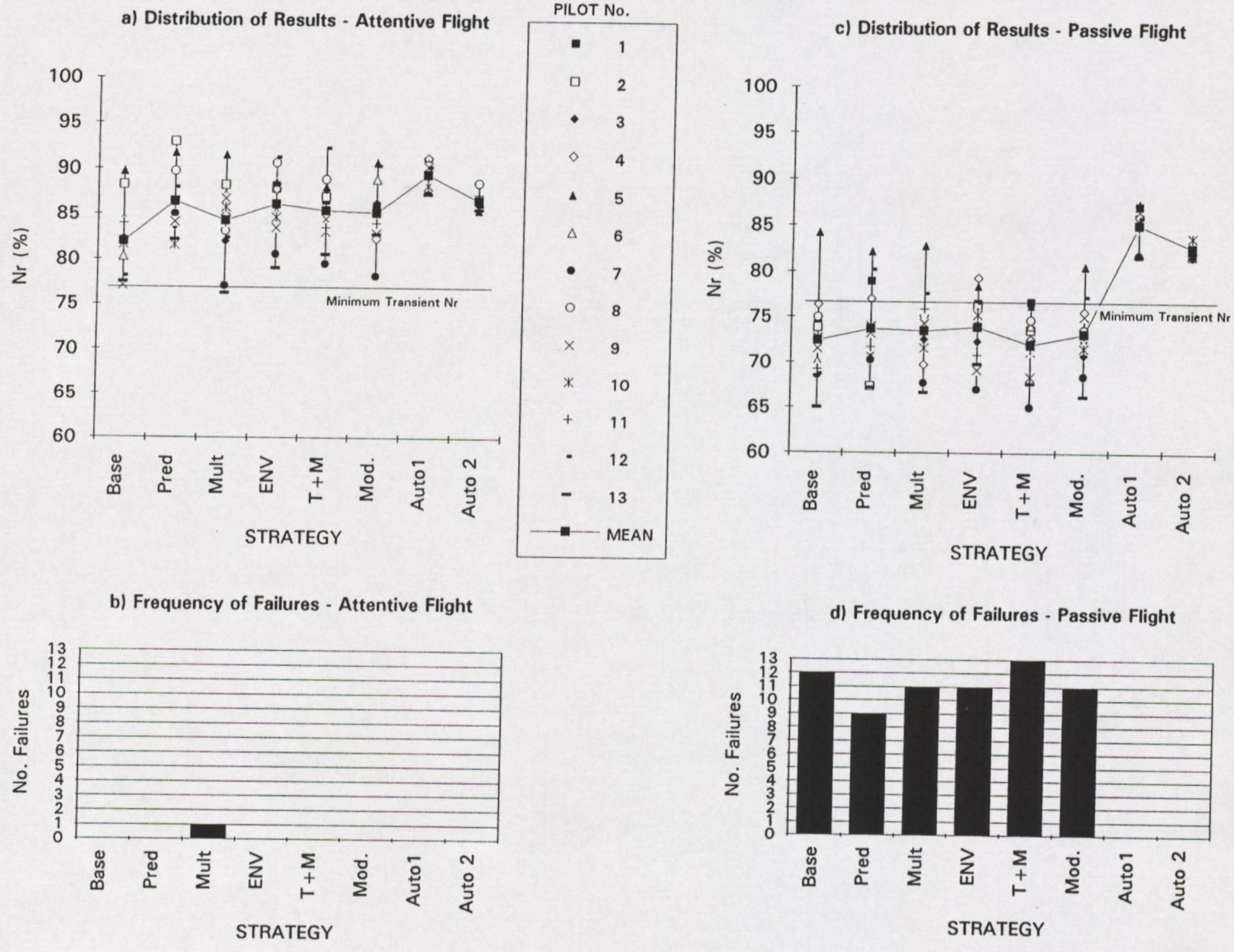


Figure 18 Distribution of Minimum Nr Reached for Each Strategy

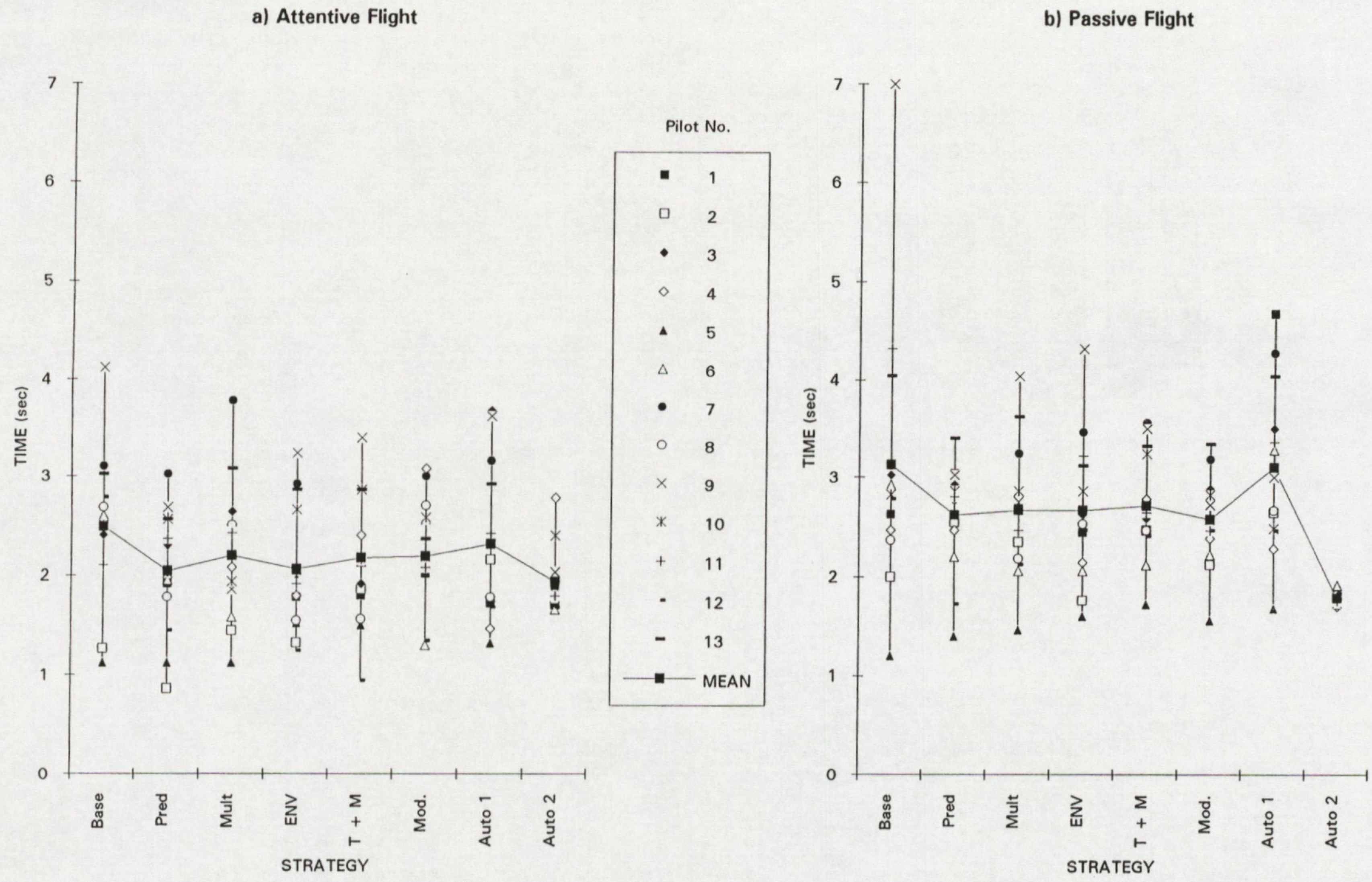


Figure 19 Time to Minimum Collective Position

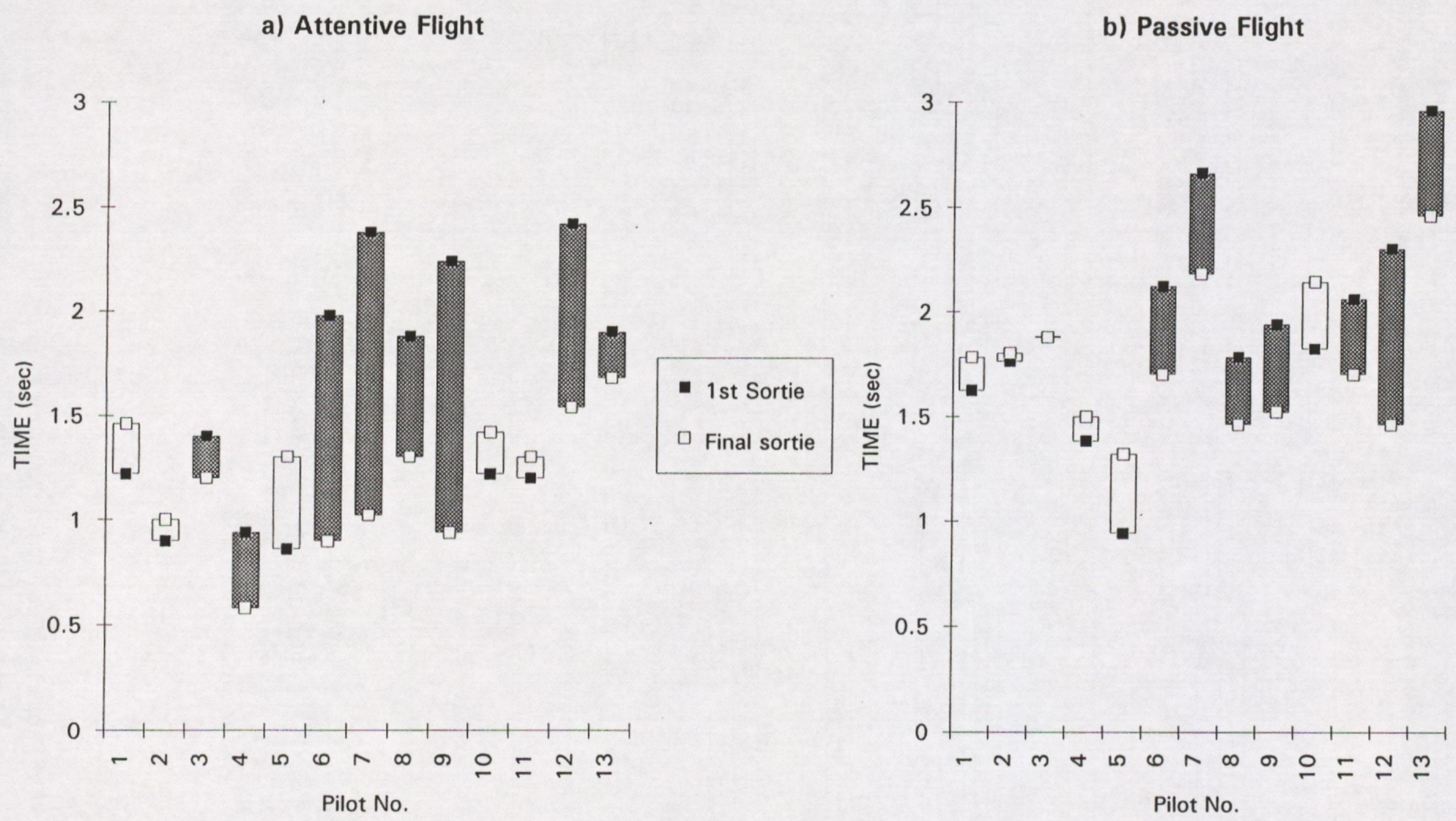
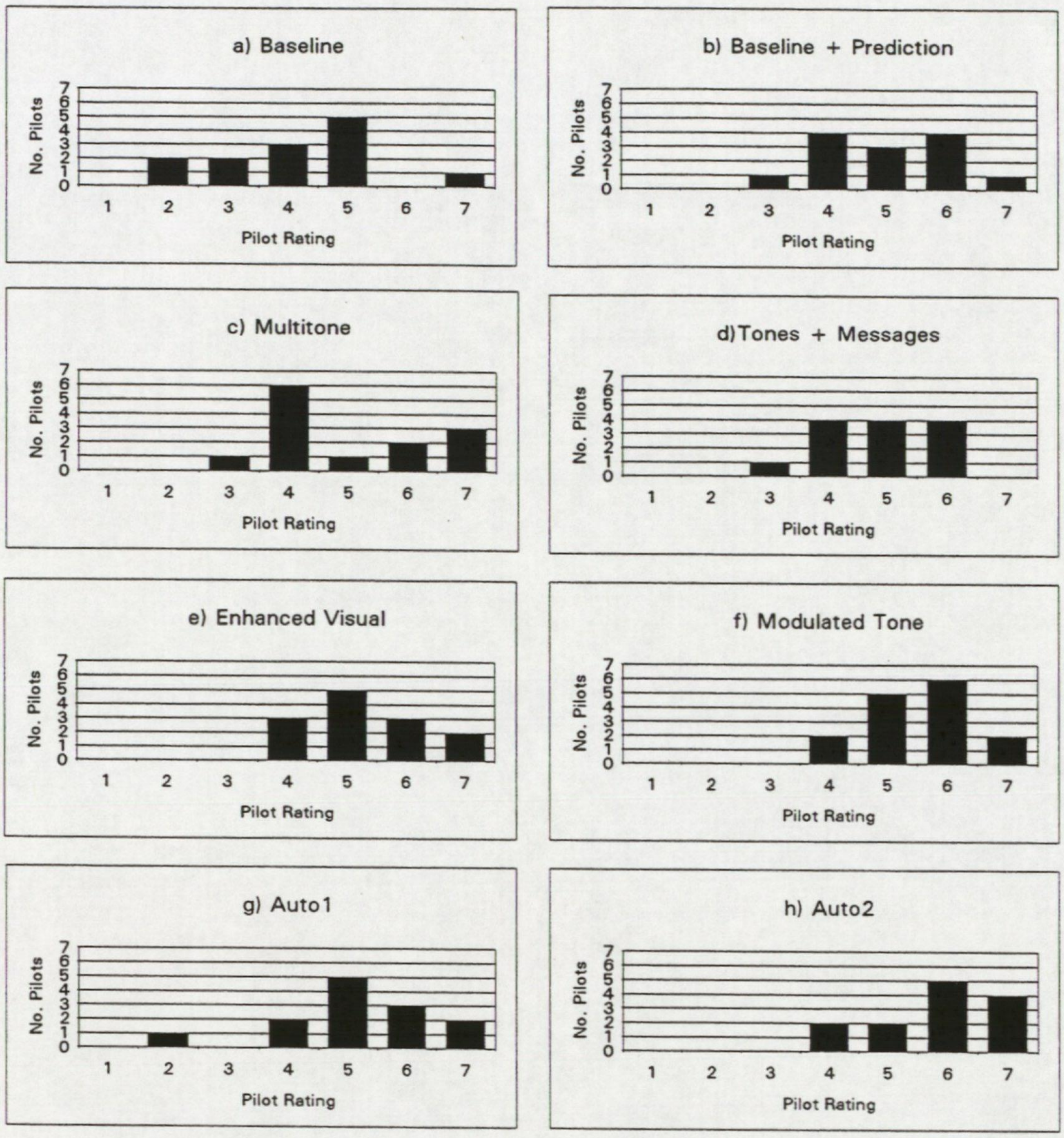
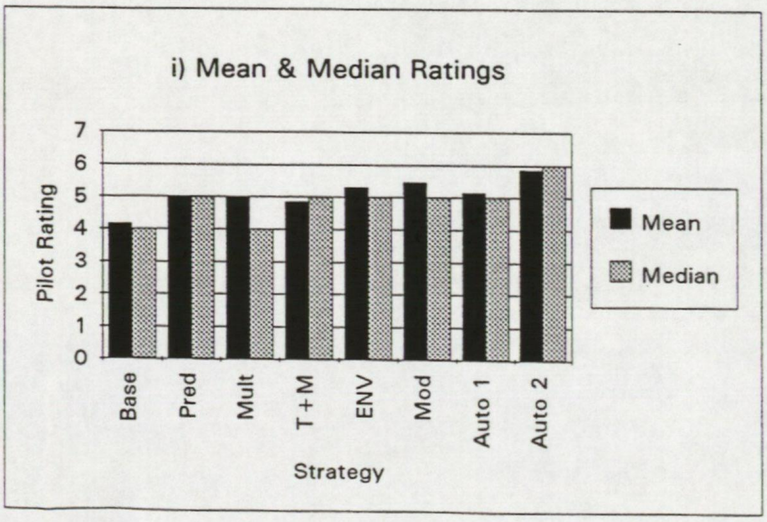


Figure 20 Practice Effects



(1- Very poor 7 - Excellent)



$$\chi r^2 = \left[\frac{12}{NC(C+1)} \Sigma T_C{}^2 \right] - 3N(C+1)$$

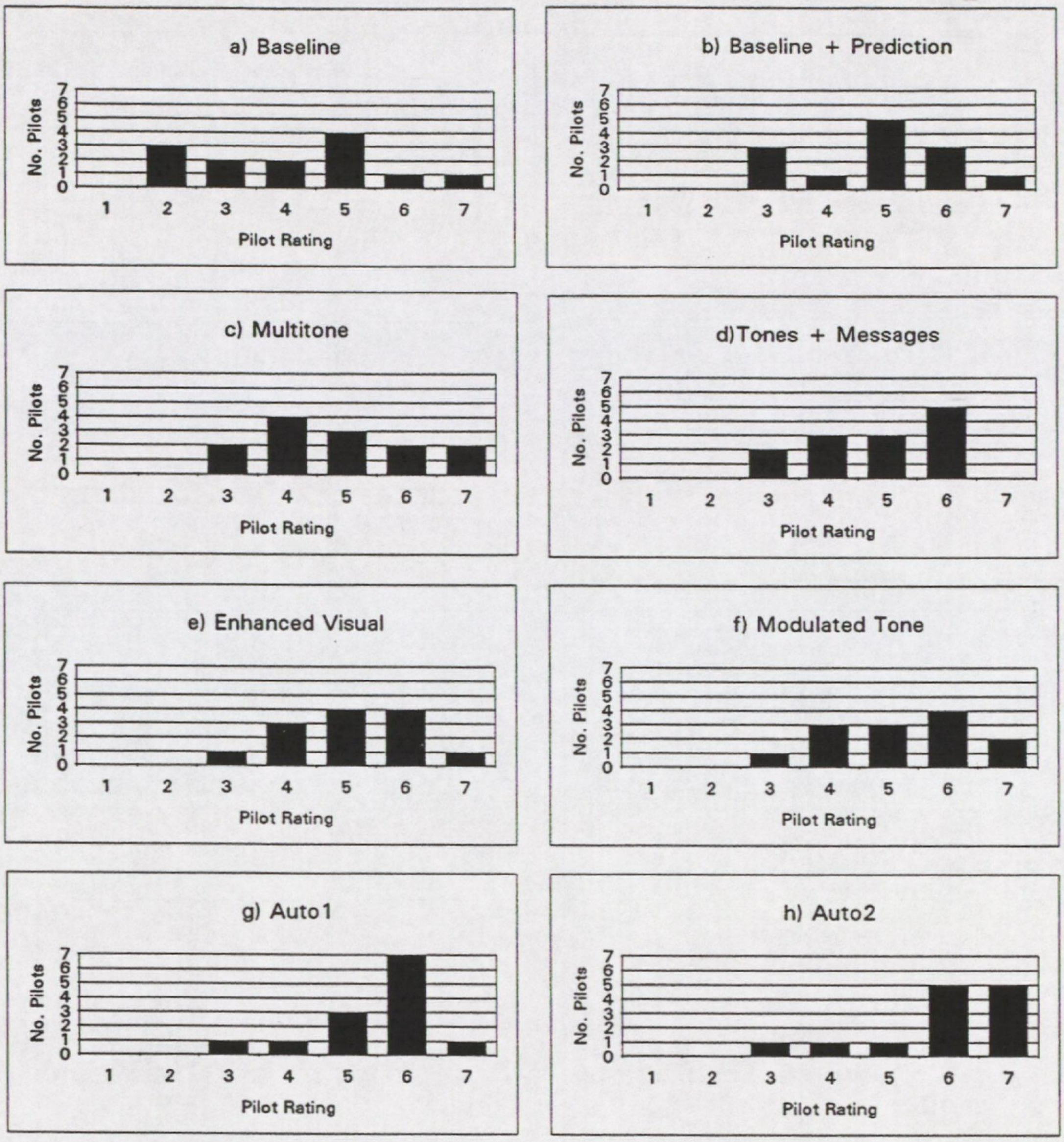
where: C = number of conditions = 8
N = number of subjects = 13
$\Sigma T_C{}^2$ = total of squared rank for each condition = 28494

$$\chi r^2 = \left[\frac{12}{13 \times 8(9)} \times 28494 \right] - 39(9)$$

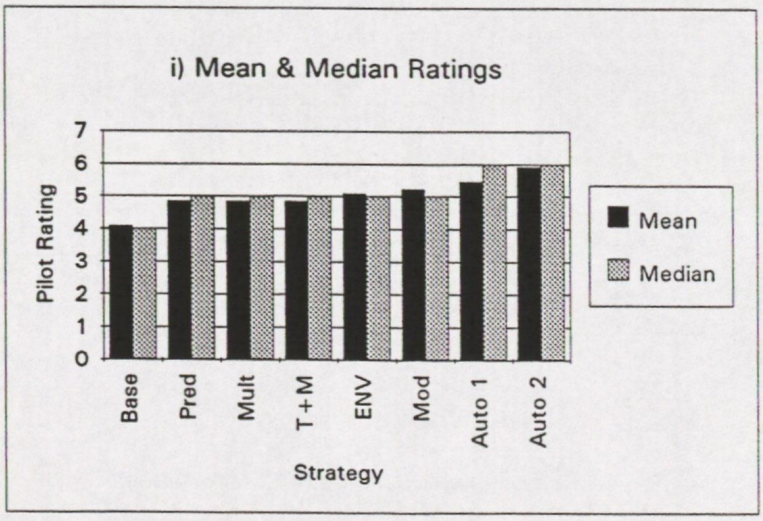
$$\chi r^2 = 365.31 - 351$$

$$\chi r^2 = 14.31, \ df = 7, \ (p < 0.05)$$

Figure 21 Pilot Subjective Ratings for Question 1
(Q1: Give an overall rating for the rotor speed loss warning strategy under attentive flight conditions.)



(1- Very poor 7 - Excellent)



$$\chi r^2 = \left[\frac{12}{NC(C+1)} \Sigma Tc^2 \right] - 3N(C+1)$$

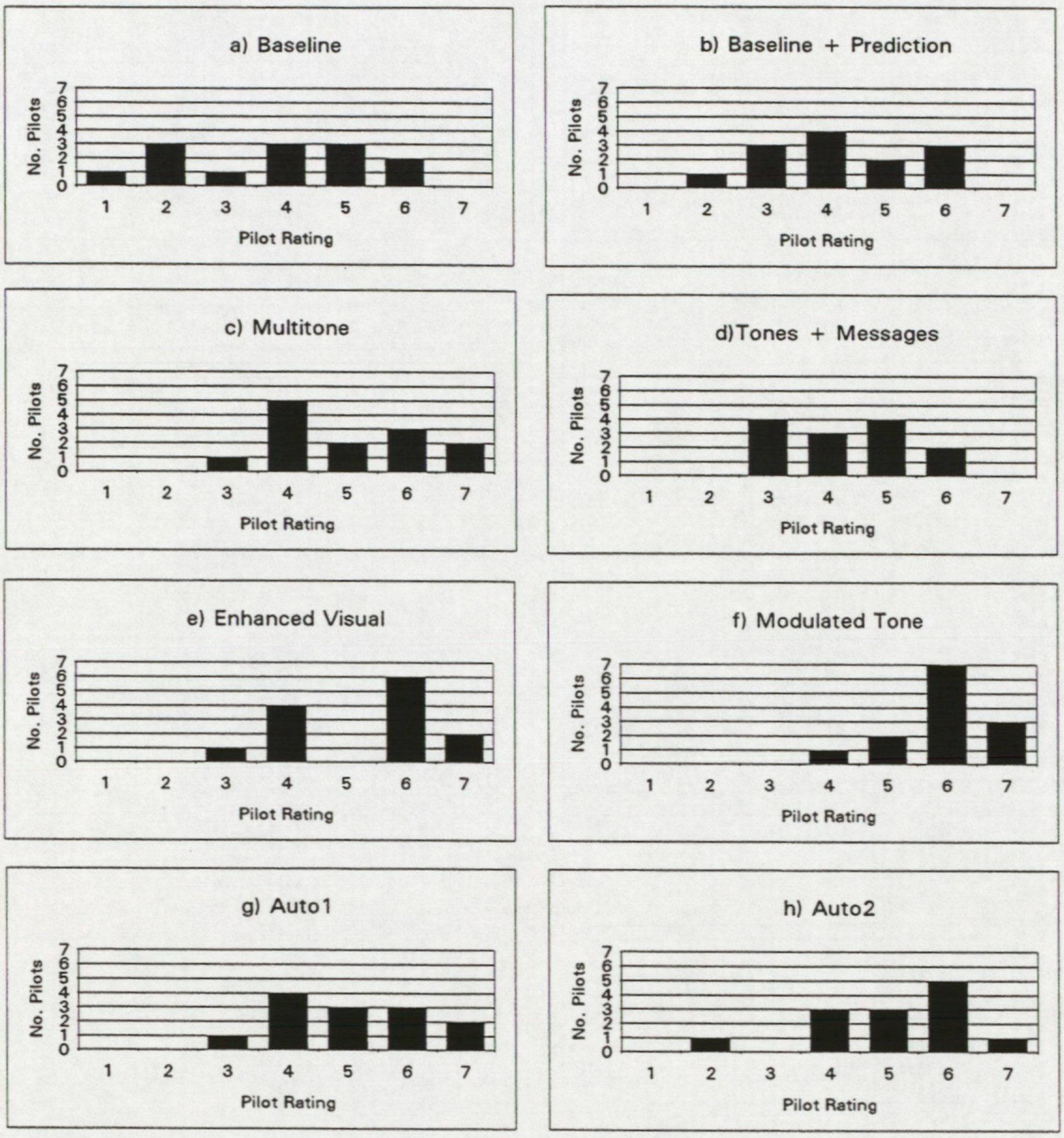
where: C = number of conditions = 8
N = number of subjects = 13
ΣTc^2 = total of squared rank for each condition = 28449

$$\chi r^2 = \left[\frac{12}{13 \times 8(9)} \times 28449 \right] - 39(9)$$

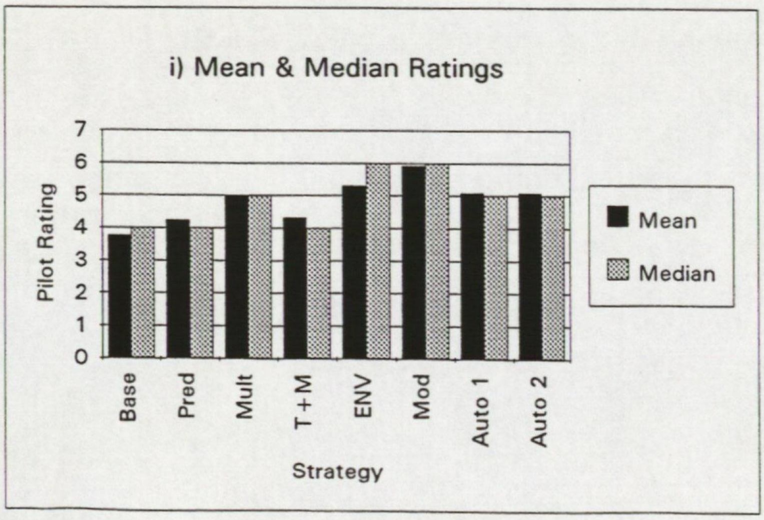
$$\chi r^2 = 364.74 - 351$$

$$\chi r^2 = 13.74, \ df = 7, \ (p < 0.10)$$

Figure 22 Pilot Subjective Ratings for Question 4
(Q4: Give an overall rating for the rotor speed loss warning strategy under passive flight conditions.)



(1- Very poor 7 - Excellent)



$$\chi r^2 = \left[\frac{12}{NC(C+1)} \Sigma T_c{}^2 \right] - 3N(C+1)$$

where: C = number of conditions = 8

N = number of subjects = 13

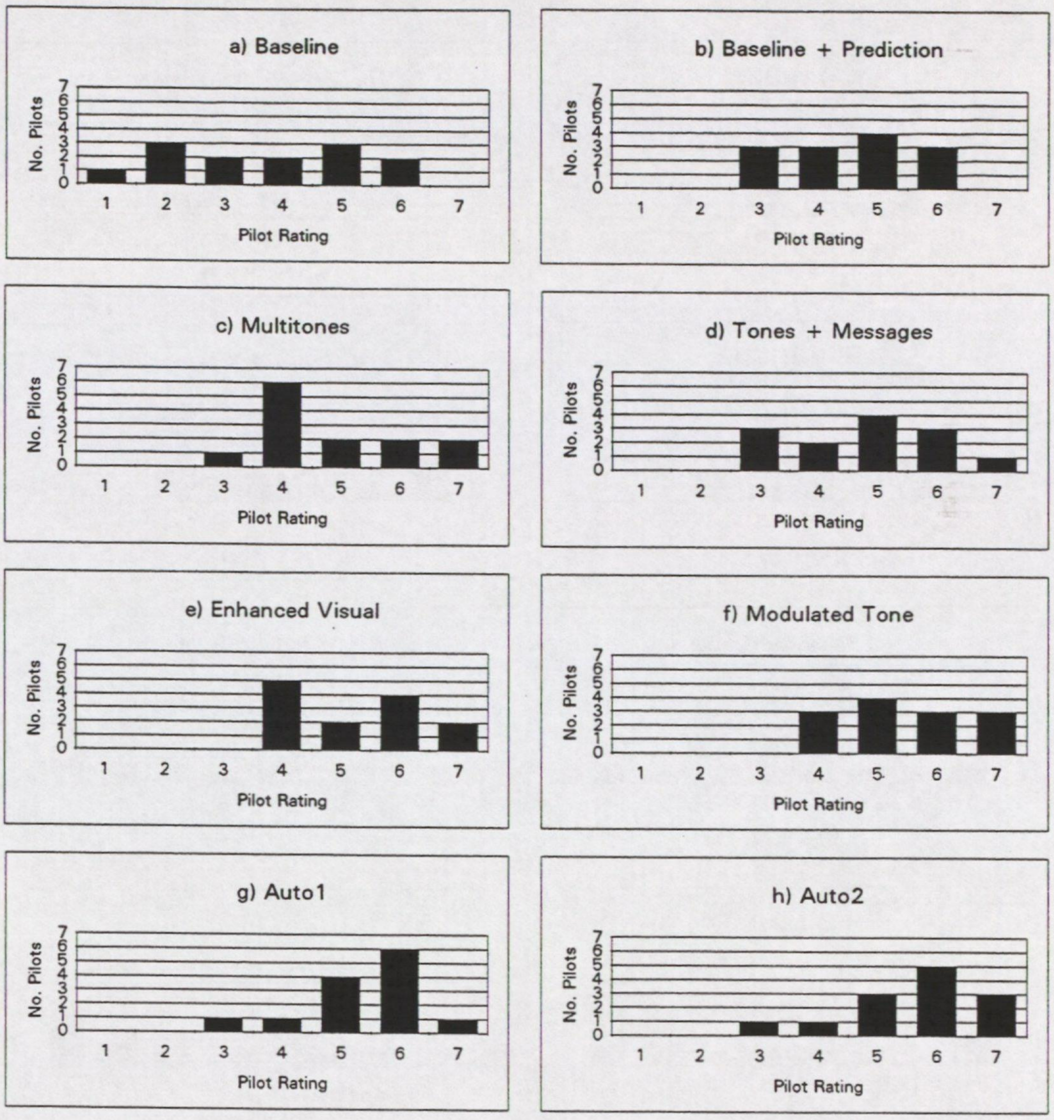
$\Sigma T_c{}^2$ = total of squared rank for each condition = 29413

$$\chi r^2 = \left[\frac{12}{13 \times 8(9)} \times 29413 \right] - 39(9)$$

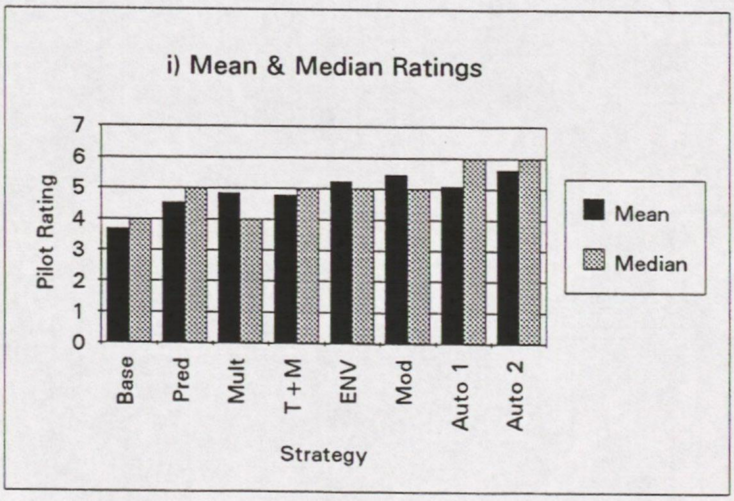
$$\chi r^2 = 377.09 - 351$$

$$\chi r^2 = 26.09, \ df = 7, \ (p < 0.001)$$

Figure 23 Pilot Subjective Ratings for Question 8
(Q8: Rate the strategy for aiding rotor speed control in autorotative flight.)



(1 - Very poor 7 - Excellent)



$$\chi r^2 = \left[\frac{12}{NC(C+1)} \Sigma Tc^2 \right] - 3N(C+1)$$

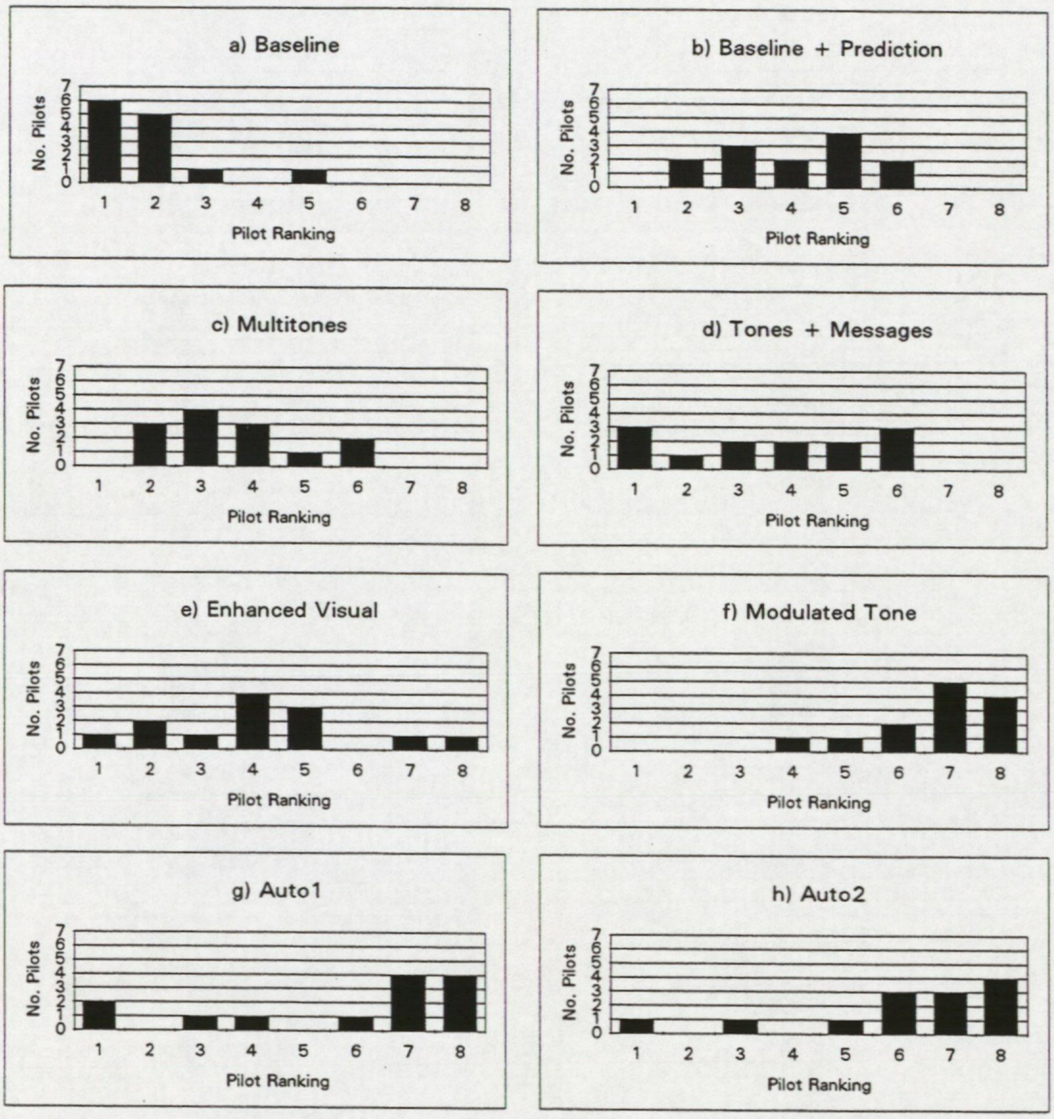
where: C = number of conditions = 8
N = number of subjects = 13
ΣTc^2 = total of squared rank for each condition = 29093

$$\chi r^2 = \left[\frac{12}{13 \times 8(9)} \times 29093 \right] - 39(9)$$

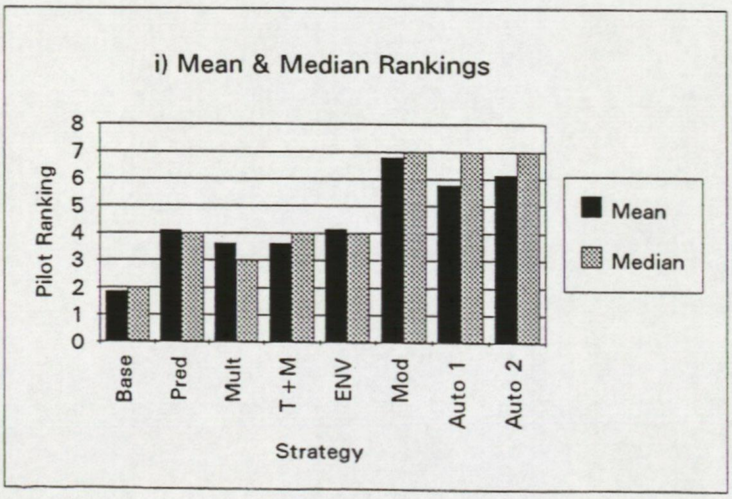
$$\chi r^2 = 372.99 - 351$$

$$\chi r^2 = 21.99, \ df = 7, \ (p < 0.01)$$

Figure 24 Pilot Subjective Ratings for Question 12
(Q12: Give an overall rating for the rotor speed loss warning strategy under both flight conditions.)



(1 - Worst system 8 - Best system)



$$\chi r^2 = \left[\frac{12}{NC(C+1)} \Sigma Tc^2 \right] - 3N(C+1)$$

where: C = number of conditions = 8
N = number of subjects = 13
ΣTc^2 = total of squared rank for each condition = 30488

$$\chi r^2 = \left[\frac{12}{13 \times 8(9)} \times 30488 \right] - 39(9)$$

$$\chi r^2 = 390.87 - 351$$

$$\chi r^2 = 39.87, \ df = 7, \ (p < 0.001)$$

Figure 25 Relative Subjective Rankings
(Question: Indicate your order of preference for the warning strategies presented during this trial.)

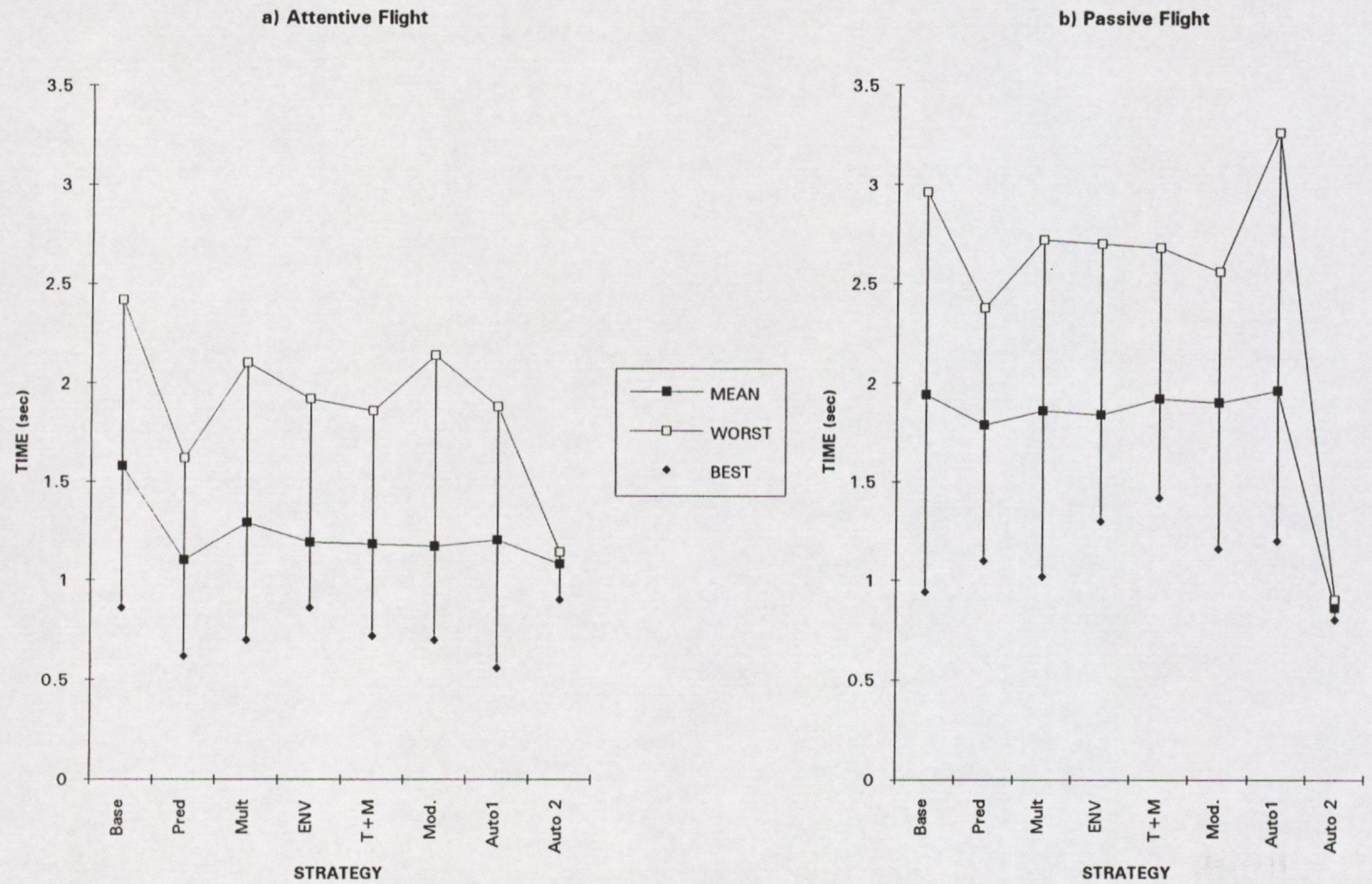


Figure 26 Actual Intervention Time Data – Worst Pilot Philosophy

Appendices

Appendix 1 Definition of Terms Used

This Appendix defines unambiguously the convention adopted in this document to describe the pilot's involvement and the elements which make up the intervention time. A review of civil airworthiness documentation revealed no suitable definition of terms, therefore the convention is based on the military standards.

DEF STAN 00-970, VOLUME 2, CHAPTER 604

12 PILOT INVOLVEMENT

12.1 In specifying the intervention times that must be demonstrated during flight testing, various levels of Pilot Involvement in the flying task have been defined as follows:

12.1.1 ACTIVE FLIGHT Any flight segment during which the characteristics of the rotorcraft and its autostabiliser necessitate continuous flying of the rotorcraft by the pilot via the flying controls; for example take-off, and tactical low flying.

12.1.2 ATTENTIVE FLIGHT Any flight segment requiring particular attention from the pilot for short periods; for example automatic approach, automatic hovering, and short periods of instrument flight.

12.1.3 PASSIVE FLIGHT Any flight segment of long duration requiring the minimum of attention from the pilot; for example cruise or long periods of instrument flight using autopilot holds.

12.2 The 'Attentive' and 'Passive' phases of flight can be further sub-divided into 'Hands-on' and 'Hands-off' the latter being applicable if the role of the rotorcraft demands that the pilot shall be able to release the flying controls for substantial periods of time.

13 TIMES AND PERIODS

13.1 Rotorcraft Response Time: This is the period between the failure occurring and the pilot being alerted to it by a suitable cue. The cue may take the form of an adequate tactile, audio or visual warning, the latter being in the central warning facility (the eye cannot be relied upon to distinguish abnormal instrument indications sufficiently early for these to be regarded as an adequate cue). In the absence of the cues listed above it can be assumed that a pilot will be alerted when either acceleration along any axis or a change in the rate of rotation in any plane exceeds a specified level. (See Appendix 4)

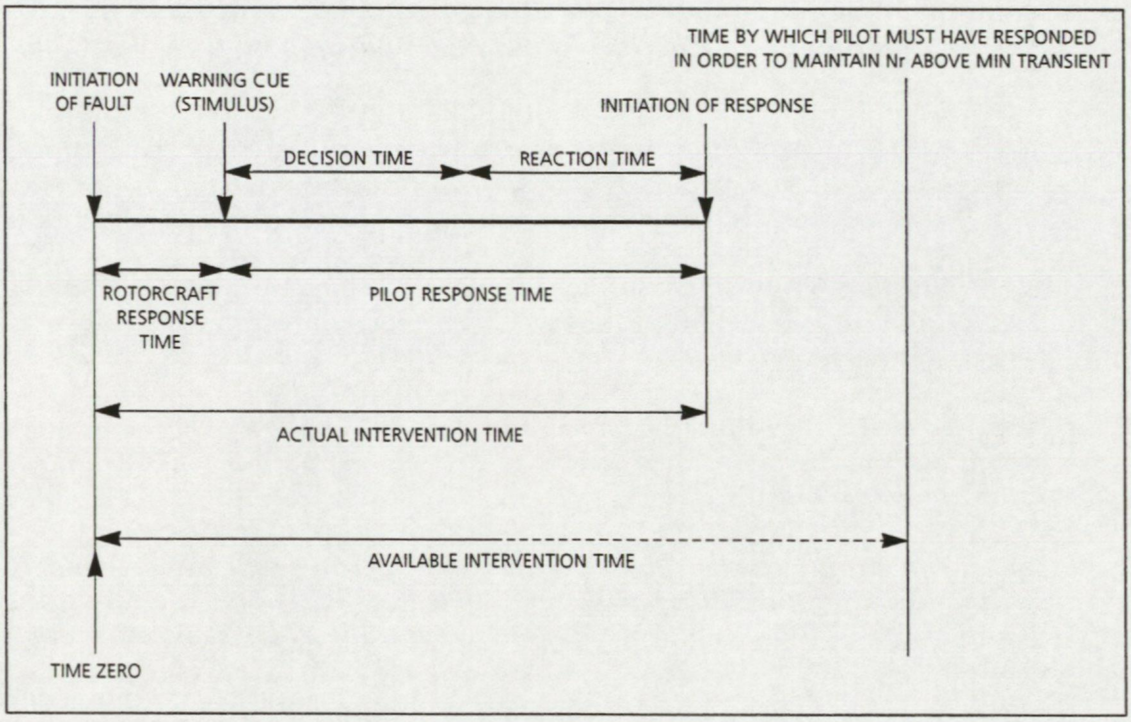
13.2 Pilot Response Time: This period commences at the time the pilot is cued to the fact that something abnormal is happening and terminates when the controls are moved to commence the recovery manoeuvre. The period consists of the decision time plus the reaction time. The decision time is assumed to increase as the pilot relaxes his involvement level. The reaction time is longer for 'hands-off' than 'hands-on' as the pilot has to locate the controls before he can move them.

13.3 *Intervention Time: The total time (i.e. rotorcraft response time plus Pilot Response Time) between failure and commencement of control movement to effect recovery.*

The convention is slightly modified in this document, with the 'intervention time' defined in 13.3 being referred to as the 'actual intervention time' as opposed to the 'available intervention time', as defined below.

Available intervention time: This is the period between the failure occurring and the pilot having to make an input in order that the rotor speed does not fall below its minimum transient limit.

The notation is summarised in the diagram below.



Appendix 2 W30 Flight Control System

The primary flight control system (FCS) for the W30 consists of conventional collective and cyclic controls, with pedals to control the yaw axis. Mechanical push rods and cables from the pilot's controls are mixed to reduce cross-coupling effects prior to entry into the hydraulic servo control units mounted on the main gearbox and tail gearbox. These servos control the main hydraulic actuators, and hence the pitch of the blades, via a mechanical pitch change mechanism. The design of the control linkages will not transmit the high control loads to the crew, with artificial feel being provided from a spring feel unit.

In addition to the primary flight control system, the W30 is fitted with the Louis Newmark plc LN400 autostabilisation equipment (ASE). This duplex analogue system provides the following features:

1	Collective	–	Collective acceleration control (CAC) + height hold
2	Pitch	–	rate damping + attitude hold
3	Roll	–	rate damping + attitude hold
4	Yaw	–	rate damping/lateral acceleration + heading hold

When the ASE is selected, all the features become active together with the exception of the height hold, which is individually selectable on the pilot's controller, and the heading hold. The heading hold is activated once the pilot removes his feet from the pedals and may be adjusted by use of the yaw trim switch on the pilot's controller. The ASE provides stability augmentation in all four channels and maintains the aircraft's height and heading at the time of engagement. It functions by monitoring reference inputs, (rate gyros, accelerometers, the compass system, etc.), and processes this information within the FCS computers to create a demand signal which is then sent to the FCS actuators.

The FCS actuators provide the interfaces between the ASE and the primary flight control system. On the W30 these take the form of duplicate electro-hydraulic series actuators and a single electro-mechanical parallel actuator in each axis. The FCS series actuators have a limited, (approximately ±10%), authority over the flying control movement. The output from the FCS series actuators is summed with the primary flight control demand within the servo control units.

Demands from the ASE which result in FCS series actuator movements, do not move the pilot's flying controls. If the ASE demand is great however, the low frequency part of the signal is fed to the parallel actuator which will retrim the aircraft and cause the pilot's controls to be back driven. Movement of the parallel actuators tends to re-centre the series actuators and restore their full range of movement, allowing the aircraft to be flown hands-off for long periods of time. A force sense link in the pilots controls will ensure that the ASE minimises any opposition to the pilot's input, while still providing the degree of damping required to maintain aircraft stability.

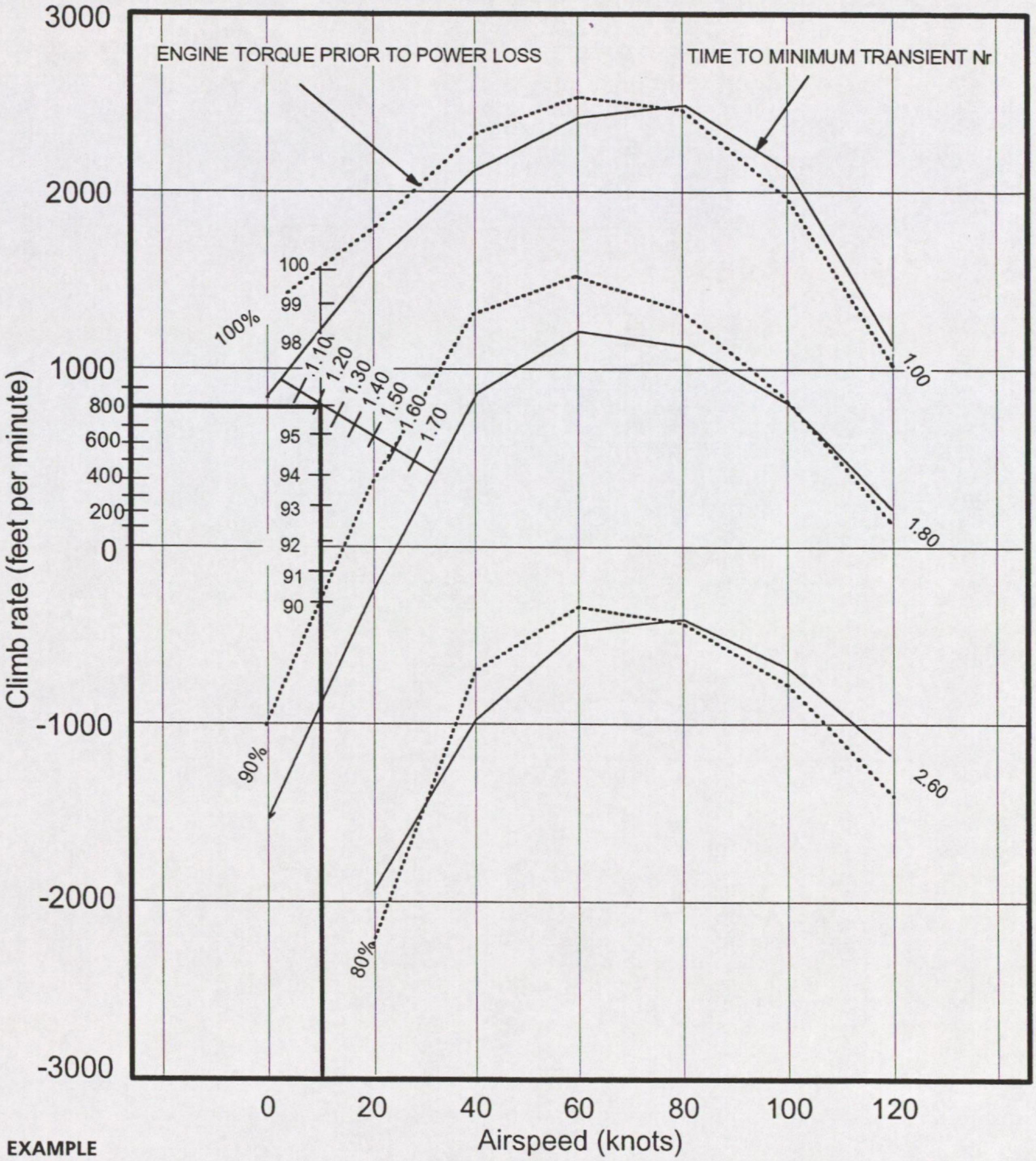
The parallel actuators, which have full authority but are slow acting, will also act as auto-trimmers. The pilot can then manoeuvre the aircraft by either of the following methods.

1 Move the controls against the spring feel unit with the trim position fixed. The aircraft will then return automatically to the same datum on the pilot releasing the control: (used for short term manoeuvres with no change to the position of the FCS actuators).

2 By pressing the trim release button, move the parallel actuators to a new trim position: (used to swiftly update the long term trim).

3 In the cyclic channels, a beep trim is provided to allow the pilot to make fine adjustments to the trim by slowly changing the parallel actuator positions, or can be used in conjunction with a control movement as another means of achieving large rapid datum changes.

Appendix 3 Example figure illustrating how to extract the time to Minimum Transient Nr from Figures 2–11



EXAMPLE

For a climb rate of 800 ft/min and an airspeed of 10 knots, the required engine torque is 96% and the time to the minimum transient Nr limit is 1·20 seconds

(Values are for illustration only)

Appendix 4 Military Specification of Pilot Intervention Times

DEF STAN 00-970, VOLUME 2, CHAPTER 604

30 ROTORCRAFT RESPONSE TIMES

30.1 For Active and Attentive flight segments the rotorcraft response time shall be the least of:

(i) the time it takes for the rotorcraft to achieve an angular rate of change about any axis of 3° per second,

(ii) the time it takes for the rotorcraft to increase or decrease acceleration along any axis by 0·2 g,

(iii) the time it takes for the relevant attention-getter to function.

30.2 For Passive flight segments the rotorcraft response time shall be the least of (i) (ii) and (iii) above except that the angular rate-of-change shall be 5° per second and the acceleration shall be 0·25g.

31 PILOT RESPONSE TIMES

Flight Segment	*Decision Time (Sec)*	*Reaction Time (Sec)*	*Pilot Response Time (Sec)*
Active	–	*0·5*	*0·5*
Attentive Hands on	*1·0*	*0·5*	*1·5*
Attentive Hands off	*1·5*	*1·0*	*2·5*
Passive Hands on	*2·0*	*0·5*	*2·5*
Passive Hands off	*3·0*	*1·0*	*4·0*

Appendix 5 Pilot-in-the-Loop Experimental Design

A5.1 SUBJECTS

Thirteen pilot subjects took part in the experiment. All held helicopter licences, and the test subjects were drawn from all areas of civil helicopter operations, including: test pilots, commercial pilots, corporate pilots, regulatory pilots and private helicopter pilots. A summary of the subjects experience is detailed in the following table.

SUMMARY OF PILOT EXPERIENCE

Pilot[8]	*Age*	*Type of Licence Held*	*Total Hours*	*Average Hours Per Annum*	*Engine Failure Experience*			*Previous Simulator Experience*
					Singles	*Twins*		
						Single	*Double*	
1	38	ATPL(H)	9300	200	YES	YES	NO	YES
2	42	ATPL(H)	5900	250	NO	YES	NO	YES
3	51	ATPL(H)	7007	250	YES	YES	NO	YES
4	32	PPL(H)	560	120	NO	NO	NO	YES
5	42	ATPL(H)	6000	150	YES	NO	NO	YES
6	46	ATPL(H)	5000	110	NO	NO	NO	YES
7	47	ATPL(H)	>8000	500	NO	NO	NO	YES
8	48	ATPL(H)	6300	600	NO	NO	NO	NO
9	55	ATPL(H)	7000	?	YES	YES	NO	YES
10	44	ATPL(H)	8300	550	NO	YES	NO	YES
11	30	ATPL(H)	3170	650	NO	NO	NO	YES
12	49	ATPL(H)	>7000	100	YES	YES	NO	YES
13	41	ATPL(H)	2700	10	NO	YES	NO	NO
Mean	**43·5**	**TOTAL 12 ATPL 1 PPL**	**>5864**	**>316·4**	**TOTAL 5**	**TOTAL 7**	**TOTAL 0**	**YES =11 NO=2**
Std Dev	**7·15**		**>2458**	**>214**				

[8] The pilot number used here is for reference purposes only, and bears no relation to the pilot numbering used in any of the tables or in the ordering in the list of acknowledgements.

A5.2 BRIEFING

Subjects were fully briefed on the nature of this trial prior to taking part. It was felt that any attempt to conceal the objectives of the trial would just increase the time necessary to perform the trial and add further complexity. Because of the nature of the trial, its objectives would also quickly become apparent to the pilots, whose responses would change as they progressed and became more familiar with the failure cases.

On arrival, the pilots were briefed on the experimental procedure. The warning strategies to be examined were explained to them in detail along with the procedures they were required to adopt in response to each of them. This briefing was conducted according to a standard format to ensure all subjects were provided with the same information.

The pilots were briefed on the secondary task (described further in Section A5.5) and instructed that they would be required to continuously perform this task during the passive flight element of each sortie. While flying passively, the pilots were expected to scan instruments and the outside world at a rate comparable to their normal operational procedures. Pilots may have been required to go hands-on during the passive element for short periods to manoeuvre the helicopter in response to ATC instructions. (Failures were not initiated during these periods).

The pilots were told that following each sortie they would be required to complete a short questionnaire. The trials controller went through the questionnaire with each pilot subject prior to the trial to explain any items which they were unsure of. This also served the purpose of emphasising the issues to which the pilots should attend during the sorties.

A5.3 DEMONSTRATION/PRACTICE

Following the initial briefing room session, the warnings and experimental procedures were demonstrated to the subjects while they were sitting in the simulator. The pilots were then allowed a period of free flying time during which they could become acquainted with the simulator and its handling characteristics. Following this, the pilots were given a period of practice with each of the warning systems to be evaluated, and they were required to fly the tasks to be used in the experiment. Subjects were also given time to practise the secondary tasks in combination with the flying tasks. Progression to the main experiment was dependent on individual subjects demonstrating a level of proficiency at the flying tasks that satisfied the trials controller.

A5.4 EXPERIMENTAL SORTIE

The subjects were required to assess each of the 7 enhanced features plus the baseline configuration, making 8 experimental sorties in total. During each sortie a single rotor speed warning strategy was evaluated. The order of presentation of each strategy was randomised for each subject.

Within any single sortie, as well as the target rotor speed warning strategy, the pilot was presented with two other 'dummy' warnings (hydraulics and fire). The order of presentation of these warnings was pseudo random, conforming to a known overall pattern, such that the pilot could never be certain of the succeeding warning or the total number of failure cases within a sortie.

The structure of the experiment is illustrated in the following table. The R, 1 and 2 corresponding to 'Rotor speed', 'Hydraulics' and 'Fire' warnings respectively.

SEQUENCE OF LOW ROTOR SPEED, FIRE AND HYDRAULICS WARNINGS													
PILOT No.		*TYPE OF LOW ROTOR SPEED WARNING*	*1*	*2*	*3*	*4*	*5*		*1*	*2*	*3*	*4*	*5*
			Attentive						Passive				
1	1	BASELINE	2	R					2	2	2	R	
	2	MULTITONES	2	2	2	R			2	2	R		
	3	TONES + MESSAGE	2	1	2	2	R		2	1	R		
	4	MODULATED TONE	1	2	2	R			2	R			
	5	ENHANCED VISUAL	1	1	1	1	R		1	R			
	6	AUTO INTERVENTION 2	2	R					1	2	2	2	R
	7	BASELINE + PREDICTION	1	1	R				1	1	2	R	
	8	AUTO INTERVENTION 1	2	2	R				2	2	2	2	R
	9	BASELINE	R						R				
			Passive						Attentive				
2	1	MODULATED TONE	1	1	1	R			1	2	R		
	2	AUTO INTERVENTION 1	1	2	R				2	1	1	1	R
	3	TONES + MESSAGE	1	1	1	2	R		2	R			
	4	MULTITONES	2	2	2	R			2	1	1	2	R
	5	ENHANCED VISUAL	2	1	1	1	R		1	2	2	R	
	6	BASELINE	1	R					1	1	1	R	
	7	BASELINE + PREDICTION	2	1	R				1	R			
	8	AUTO INTERVENTION 2	2	R					1	2	R		
	9	MODULATED TONE	R						R				
			Attentive						Passive				
3	1	BASELINE + PREDICTION	1	2	R				1	2	1	R	
	2	ENHANCED VISUAL	1	2	1	2	R		2	2	2	1	R
	3	TONES + MESSAGE	1	2	1	2	R		2	R			
	4	AUTO INTERVENTION 2	1	R					1	R			
	5	MULTITONES	2	2	2	R			2	1	R		
	6	MODULATED TONE	2	1	2	R			2	1	2	2	R
	7	BASELINE	2	R					1	1	1	R	
	8	AUTO INTERVENTION 1	2	2	R				2	1	R		
	9	BASELINE + PREDICTION	R						R				
			Passive						Attentive				
4	1	BASELINE	1	R					2	1	2	R	
	2	MODULATED TONE	1	2	2	R			1	R			
	3	ENHANCED VISUAL	1	2	1	1	R		1	R			
	4	AUTO INTERVENTION 1	2	2	R				1	2	2	R	
	5	BASELINE + PREDICTION	2	2	R				2	1	2	1	R
	6	AUTO INTERVENTION 2	2	R					2	2	1	1	R
	7	TONES + MESSAGE	2	2	1	1	R		1	1	R		
	8	MULTITONES	2	2	1	R			2	2	R		
	9	BASELINE	R						R				

SEQUENCE OF LOW ROTOR SPEED, FIRE AND HYDRAULICS WARNINGS

PILOT No.		*TYPE OF LOW ROTOR SPEED WARNING*	*1*	*2*	*3*	*4*	*5*		*1*	*2*	*3*	*4*	*5*
			Attentive						Passive				
5	1	AUTO INTERVENTION 1	2	2	R				2	1	1	R	
	2	TONES + MESSAGE	2	2	1	2	R		1	1	2	2	R
	3	ENHANCED VISUAL	1	2	2	1	R		2	R			
	4	MULTITONES	1	2	2	R			2	2	R		
	5	MODULATED TONE	1	2	1	R			2	2	1	1	R
	6	AUTO INTERVENTION 2	2	R					2	1	R		
	7	BASELINE + PREDICTION	2	2	R				1	R			
	8	BASELINE	1	R					2	2	1	R	
	9	AUTO INTERVENTION 1	R						R				
			Passive						Attentive				
6	1	BASELINE + PREDICTION	1	1	R				2	1	1	R	
	2	ENHANCED VISUAL	2	2	1	2	R		1	1	R		
	3	BASELINE	1	R					2	2	R		
	4	TONES + MESSAGE	1	1	1	2	R		2	R			
	5	AUTO INTERVENTION 2	2	R					2	R			
	6	MULTITONES	2	2	2	R			1	2	1	2	R
	7	AUTO INTERVENTION 1	1	2	R				2	1	2	R	
	8	MODULATED TONE	2	2	2	R			2	2	1	1	R
	9	BASELINE + PREDICTION	R						R				
			Attentive						Passive				
7	1	ENHANCED VISUAL	2	2	1	1	R		2	1	R		
	2	TONES + MESSAGE	1	2	2	2	R		1	1	1	1	R
	3	MULTITONES	2	1	2	R			2	R			
	4	MODULATED TONE	1	1	1	R			1	1	1	2	R
	5	AUTO INTERVENTION 2	1	R					2	2	1	R	
	6	AUTO INTERVENTION 1	2	1	R				2	2	1	R	
	7	BASELINE	2	R					1	R			
	8	BASELINE + PREDICTION	1	2	R				1	2	R		
	9	ENHANCED VISUAL	R						R				
			Passive						Attentive				
8	1	AUTO INTERVENTION 1	1	2	R				2	1	1	R	
	2	AUTO INTERVENTION 2	2	R					1	2	1	1	R
	3	ENHANCED VISUAL	1	2	2	1	R		2	R			
	4	BASELINE + PREDICTION	1	2	R				2	R			
	5	MODULATED TONE	2	2	2	R			1	2	R		
	6	MULTITONES	1	1	2	R			2	1	2	1	R
	7	BASELINE	1	R					2	1	1	R	
	8	TONES + MESSAGE	1	1	1	2	R		2	2	R		
	9	AUTO INTERVENTION 1	R						R				

SEQUENCE OF LOW ROTOR SPEED, FIRE AND HYDRAULICS WARNINGS												
PILOT No.		*TYPE OF LOW ROTOR SPEED WARNING*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
			Attentive					Passive				
9	1	AUTO INTERVENTION 1	1	1	R			2	2	1	R	
	2	ENHANCED VISUAL	2	1	1	2	R	2	R			
	3	MULTITONES	1	1	1	R		2	R			
	4	BASELINE + PREDICTION	2	1	R			1	2	1	R	
	5	AUTO INTERVENTION 2	1	R				2	1	2	2	R
	6	BASELINE	2	R				1	2	2	1	R
	7	TONES + MESSAGE	2	2	1	1	R	1	2	R		
	8	MODULATED TONE	1	2	2	R		2	1	R		
	9	AUTO INTERVENTION 1	R					R				
			Passive					Attentive				
10	1	AUTO INTERVENTION 1	2	1	R			1	2	2	R	
	2	BASELINE + PREDICTION	2	2	R			2	2	2	1	R
	3	TONES + MESSAGE	1	1	2	1	R	2	R			
	4	AUTO INTERVENTION 2	2	R				1	2	R		
	5	MODULATED TONE	2	2	2	R		1	1	2	1	R
	6	ENHANCED VISUAL	1	2	2	2	R	2	2	R		
	7	MULTITONES	2	2	2	R		1	R			
	8	BASELINE	1	R				2	1	1	R	
	9	AUTO INTERVENTION 1	R					R				
			Attentive					Passive				
11	1	MODULATED TONE	2	1	2	R		R				
	2	MULTITONES	1	2	1	R		2	1	R		
	3	BASELINE	1	R				1	R			
	4	AUTO INTERVENTION 2	1	R				2	1	1	2	R
	5	TONES + MESSAGE	1	1	1	2	R	1	2	R		
	6	AUTO INTERVENTION 1	2	2	R			2	1	2	1	R
	7	BASELINE + PREDICTION	2	2	R			2	R			
	8	ENHANCED VISUAL	2	2	1	2	R	1	1	1	R	
	9	MODULATED TONE	R					2	1	1	R	
			Passive					Attentive				
12	1	BASELINE	2	R				1	1	2	R	
	2	MULTITONES	2	2	2	R		1	R			
	3	AUTO INTERVENTION 1	1	1	R			1	R			
	4	TONES + MESSAGE	2	2	1	1	R	2	2	1	R	
	5	BASELINE + PREDICTION	2	1	R			1	2	2	1	R
	6	ENHANCED VISUAL	2	2	2	2	R	2	2	1	2	R
	7	MODULATED TONE	1	1	2	R		1	2	R		
	8	AUTO INTERVENTION 2	2	R				1	2	R		
	9	BASELINE	R					R				

SEQUENCE OF LOW ROTOR SPEED, FIRE AND HYDRAULICS WARNINGS													
PILOT No.		*TYPE OF LOW ROTOR SPEED WARNING*	*1*	*2*	*3*	*4*	*5*		*1*	*2*	*3*	*4*	*5*
			Attentive						Passive				
13	1	MODULATED TONE	1	1	1	R			2	1	1	R	
	2	ENHANCED VISUAL	1	2	2	2	R		2	2	2	1	R
	3	AUTO INTERVENTION 2	1	R					1	R			
	4	AUTO INTERVENTION 1	2	1	R				1	1	R		
	5	BASELINE	2	R					2	1	2	2	R
	6	MULTITONES	1	1	1	R			1	1	R		
	7	TONES + MESSAGE	2	2	1	1	R		2	R			
	8	BASELINE + PREDICTION	1	1	R				1	1	1	R	
	9	MODULATED TONE	R						R				

A5.5 SECONDARY TASK

Each sortie was conducted in two phases: attentive and passive flight scenarios. It was expected that pilots in the passive phase may be unrealistically scanning for a warning. To prevent this, secondary tasks aimed at reducing the attentiveness level of the subject pilot were devised and the pilot monitored through closed-circuit TV.

The order of completion of the attentive and passive phases were counterbalanced across all subjects.

Ideally, the secondary task should have face validity, i.e. it should be a task that pilots would normally be expected to complete in a cockpit environment. It must require the pilot to remove his hands from the controls and it should involve a reasonable degree of cognitive effort. It should also be a continuous task that can be carried on by the pilot throughout the sortie. This would prevent the pilot from pairing the instruction to commence the secondary task with the onset of a warning, thus allowing him to predict the occurrence of a warning.

The secondary task took the form of simple word association and numerical sequencing tasks. These exercises are readily available, thereby reducing the time and effort required to generate them, and meet the requirements of being a continuous task and of having a degree of cognitive effort. These tasks are not ones required in operational flying however, which may lead to some criticism, although the primary objective of distracting the pilot from his normal flying tasks was met.

Performing the secondary tasks was a two handed operation. This ensured that the pilot had both hands off the controls in the passive flight elements, and would also give a constant initial condition when comparing the pilot response times between subjects.

A5.6 EXPERIMENTAL EMERGENCY PROCEDURES

During the sortie the trials controller initiated a number of emergencies, which resulted in a warning. The fire and hydraulic warnings required the pilot to follow a series of defined procedures to indicate recognition of the fault. These procedures were briefed to the pilot during demonstration and practice and were designed to be as realistic as possible. Emergency procedure instructions are detailed below.

TOTAL POWER FAILURE/LOW Nr

1 Rapidly lower the collective lever fully to contain Nr.

2 Establish an autorotative descent at 60 knots IAS.

3 Adjust the collective to control rotor speed.

4 Adjust flight path to approach into wind (heading 180°) using approximately a rate-one turn.

5 Initiate distress procedure (Mayday) and warn crew and cabin occupants.

6 Control rotor speed within the indicated range throughout the autorotative manoeuvre and continue descent until further notice from the trials controller.

HYDRAULICS SYSTEM FAILURE

1 Check systems selector switch is in 'on' position (central).

2 Identify failed system; associated hydraulic pressure gauge reads low (less than 40 bar).

3 Switch off defective hydraulic system as appropriate:

4 Confirm the nature of the failure to trials controller and advise of all actions taken.

'No 1 system off' =Switch in fully backward position
'No 2 system off' =Switch in fully forward position

e.g. 'No 1 Hydraulic system failure, No 1 system disengaged.'

5 Trials controller cancels warning

6 When CWP caption extinguishes, return switch to central position

7 Continue flight.

FIRE WARNING

1 Identify affected engine by 'F button' illuminated on overhead console.

2 Press appropriate green extinguisher button, as illuminated on the overhead panel, to put out the fire.

3 Confirm the nature of the fire to the trials controller and advise of all actions taken. e.g. 'No 1 engine bay fire; Fire extinguished'.

4 Trials controller cancels warning.

5 Continue the flight, CWP 'FIRE' caption will extinguish.

Note to Pilots:

Hydraulic systems and fire warnings can be considered as having no continuing effect on the flight. Once cancelled the aircraft returns to a fully operational state, and further warnings, should they occur, should be dealt with in exactly the same way as described above.

All failure conditions were initiated by button presses at the trials controller's station. The low rotor speed warning was initiated by a gradual (0·7 seconds time constant) double engine failure that was introduced by the trials controller during each sortie. The pilot was required to recognise the engine failure and control the rotor speed decay by lowering the collective as fast as possible to enter into autorotative flight. Autorotative flight was then maintained during the descent and a turn of up to 180° was performed to get the aircraft into wind in preparation for landing. (Pilots were briefed that a constant strength wind of 20 kts was blowing from the south). This added further realism to the scenario as well as exciting some dynamic variation into the rotor speed. In most cases the descent was terminated by the trials controller on completion of the turn and prior to touchdown.

Following the completion of each sortie, the test subjects were required to fill in a short questionnaire that recorded their subjective attitudes towards the warning strategy they had just seen. An example of this questionnaire is included in Appendix 8. During this period the simulation was re-configured to present the next warning strategy (as dictated by the random order for that pilot).

A5.7 PRACTICE CHECK

To try to quantify the effects of training, practice and fatigue on a pilot's performance, a short sortie containing the strategy seen by the pilot in his first sortie was repeated at the end of the trial.

A5.8 DEBRIEF

After the final sortie the pilot underwent a debriefing session, where he had an opportunity to discuss the trial and give general comments. He was also asked to complete a further questionnaire which included a comparative rating of the rotor speed warning strategies that had been demonstrated. The questionnaire also allowed the pilot to document what he considered to be the ideal system. The results of this exercise are included in Appendix 8.

A5.9 NUMBER OF DATA POINTS PER SORTIE

Originally it was proposed to collect data from 3 engine failure cases on each sortie in order to allow an average score to be calculated. This increased the time required for each sortie quite considerably and therefore in an attempt to reduce the overall workload placed on each subject a single measure was decided upon. A single measure is more akin to the situation in a real aircraft where the pilot only has one chance to get it right. By providing sufficient practice the variability associated with performing the task should have been reduced, such that performance should stabilise to a consistent level.

The level of pilot involvement is a within-subjects variable, with all pilots completing attentive and passive scenarios. Mean scores for each strategy are therefore based on 13 scores per condition.

A5.10 DATA RECORDING AND PROCESSING

Aircraft and control system parameters listed in the table below, were recorded on each sortie. The initialisation of an engine failure by the controller triggered the recording of the parameters into a data file at a rate of 50 Hz for 1 minute, then at a rate of 5 Hz for the remainder of the recovery.

LIST OF RECORDED PARAMETERS FROM THE SIMULATION TRIAL

1 = TIME FROM FAILURE INITIATION (SECONDS)

PILOT RESPONSE

2 = COLLECTIVE POSITION [0 (DOWN) at 1 (UP)]
3 = PILOT COLLECTIVE INPUT (LOGICAL)
4 = COLLECTIVE TRIM RELEASE (LOGICAL)

FAILURE TYPE

5 = FAILURE SCENARIO (0-9)
    4 = GRADUAL TOTAL POWER FAILURE
    7 = HYDRAULIC FAILURE
    9 = FIRE ALERT

PILOT CUES

6 = AUDIO MESSAGE REQUEST
7 = ROTOR TONE ENABLE FLAG
8 = COLLECTIVE STICK SHAKER ACTIVATED
9 = COLLECTIVE STICK LOWERING SYSTEM ACTIVATED
10 = LOW ROTOR RPM MASTER CAUTION
11 = HIGH ROTOR RPM MASTER CAUTION
12 = RED MASTER CAUTION
13 = YELLOW MASTER CAUTION
14 = CWP < ENG FAIL>
15 = CWP < ENG 1 OIL PRESS >
16 = CWP < ENG 2 OIL PRESS >
17 = CWP < ELEC >
18 = CWP < HYD PRESS 1 >
19 = CWP <FIRE>
20 = CWP <DC ELEC >

AIRCRAFT RESPONSE

21 = % ROTOR RPM
22 = % PHASE ADVANCED ROTOR RPM
23 = % ENGINE TORQUE 1
24 = % ENGINE TORQUE 2
25 = TOTAL AIRSPEED (KNOTS)
26 = ROLL ATTITUDE (DEGREES)
27 = PITCH ATTITUDE (DEGREES)
28 = HEADING (DEGREES)

A5.11 DEPENDENT VARIABLES

From the resulting data files a number of dependent variables were extracted. These included: time of first stimuli, (or rotorcraft response time), time of first response[9], Nr at first response, minimum Nr achieved, and the time at which the minimum collective position was reached. From these parameters a number of other measures were calculated; ΔNr (change in Nr from that occurring at first response to minimum achieved Nr), time to minimum collective (time at minimum collective – time at first response), pilot response time (time at first response – time of first stimulus) and available intervention time (see discussion of calculation below).

A summary of all the data recorded for each pilot is listed in Appendix 6.

A5.12 CALCULATION OF AVAILABLE INTERVENTION TIME

Available intervention time was derived in order to illustrate the differences in time available for the pilot to make his response, dependent on the strategy used. For example, the automatic systems dramatically increased available intervention times when compared to the other systems. Available intervention time represents the time from initiation of the engine failure(s) to that by which the pilot must have started his response in order to avoid exceeding the minimum transient rotor rpm limit. This was calculated taking into account the nominal decay of rotor rpm and average individual pilot collective movement time. It was calculated as follows.

Mean ΔNr was calculated for each pilot by averaging ΔNr across the 6 manual intervention strategies (i.e. excluding Auto 1 and Auto 2).

Each pilot's mean ΔNr was then added to 76.6% (minimum transient Nr). The resulting value of Nr was then cross referenced with the data record of a post hoc trial performed with no pilot intervention. This produced a time by which each pilot must have responded in order to preserve Nr above the minimum transient limit.

This value was taken as constant for all manual strategies for each pilot. The values were then averaged over all pilots to produce a mean available intervention time for each strategy.

For the automated systems (Auto 1 and Auto 2) available intervention time was taken from post hoc trials with no pilot intervention. Under attentive flight conditions (see section 13.2 for definitions) it was found that available intervention time was >30 secs for Auto 1, and infinite for Auto 2, (i.e. no pilot response was required). Under passive flight conditions mean available intervention time remained infinite for Auto 2 but decreased to 5.4 seconds with Auto 1 strategy.

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9 To allow for different pilot strategies for collective movement, first response was defined as the first observable indication that the pilot had made an action on the collective. This could be either the first press of collective trim release, or the first movement of the collective.

A5.13 INTERPRETATION OF AVAILABLE INTERVENTION TIME

It should be borne in mind that available intervention time is an estimated value, and it is based on the assumption that recovery may be accomplished using only the collective control. The assumption is founded on the pre-trial briefing which included specific instructions that lowering the collective should be the pilot's first and immediate response.

The estimated available intervention time may increase if the pilot included a cyclic flare manoeuvre decreasing the rate of rotor rpm decay. However, this has not been quantified in this experiment.

A5.14 AUTOMATIC SYSTEM RESPONSE TIME

The data files for the automatic systems were examined in order to determine whether recorded actual intervention time data was due to the automatic system or to the pilot's reaction. The sorties on which the system had responded first were identified and the mean automatic system response time for both automatic systems were calculated. These are indicated on Figure 14.

Appendix 6 Individual Pilot Quantitative Data Record

PILOT 1

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·4	0·56	0·56	0·58	0·56	0·56	0·56	0·58
FIRST RESPONSE (Secs)	1·22	1·06	1·18	0·86	1·1	1·08	0·9	1·12
Nr AT FIRST RESPONSE (%)	93·92	95·64	94·52	98·02	95·51	95·66	97·47	95·35
MIN Nr (%)	83·9	86·35	86·59	88·2	86·61	86·07	90·95	86·65
DELTA Nr (%)	10·02	9·29	7·93	9·82	8·9	9·59	6·52	8·7
TIME AT MIN COLLECTIVE (Secs)	2·1	1·92	1·92	1·78	1·8	2·02	1·72	1·7
TIME TO MIN COLLECTIVE (Secs)	0·88	0·86	0·74	0·92	0·7	0·94	0·82	0·58
ROTORCRAFT RESPONSE TIME (Secs)	1·4	0·56	0·56	0·58	0·56	0·56	0·56	0·58
PILOT RESPONSE TIME (Secs)	–0·18	0·5	0·62	0·28	0·54	0·52	0·34	0·54
AVAILABLE INTERVENTION TIME (Secs)	2·04	2·04	2·04	2·04	2·04	2·04	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·2	0·5	0·5	0·5	0·5	0·5	0·5	0·46
FIRST RESPONSE (Secs)	1·62	1·46	1·78	1·78	1·64	2·02	1·3	0·8
Nr AT FIRST RESPONSE (%)	85·77	89·06	84·27	84·6	86·09	80·82	92·04	97·07
MIN Nr (%)	74·14	78·9	73·82	76·52	76·63	72·86	87·15	83·39
DELTA Nr (%)	11·63	10·16	10·45	8·08	9·46	7·96	4·89	13·68
TIME AT MIN COLLECTIVE (Secs)	2·62	3·04	2·68	2·44	2·46	2·74	4·68	
TIME TO MIN COLLECTIVE (Secs)	1	1·58	0·9	0·66	0·82	0·72	3·38	–0·8
ROTORCRAFT RESPONSE TIME (Secs)	1·2	0·5	0·5	0·5	0·5	0·5	0·5	0·46
PILOT RESPONSE TIME (Secs)	0·42	0·96	1·28	1·28	1·14	1·52	0·8	0·34
AVAILABLE INTERVENTION TIME (Secs)	1·6	1·6	1·6	1·6	1·6	1·6	5·4	1000

PILOT 2

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·66	0·58	0·56	0·56	0·56	0·56	0·56	0·56
FIRST RESPONSE (Secs)	0·9	0·62	0·9	1·02	1·08	1·2	1·16	1·08
Nr AT FIRST RESPONSE (%)	97·02	100·08	97·25	96·23	95·22	94·16	94·55	95·4
MIN Nr (%)	88·21	92·92	88·25	87·91	86·96	84·87	88·77	87·16
DELTA Nr (%)	8·81	7·16	9	8·32	8·26	9·29	5·78	8·24
TIME AT MIN COLLECTIVE (Secs)	1·26	0·86	1·44	1·32	1·86	2·1	2·16	1·76
TIME TO MIN COLLECTIVE (Secs)	0·36	0·24	0·54	0·3	0·78	0·9	1	0·68
ROTORCRAFT RESPONSE TIME (Secs)	1·66	0·58	0·56	0·56	0·56	0·56	0·56	0·56
PILOT RESPONSE TIME (Secs)	–0·76	0·04	0·34	0·46	0·52	0·64	0·6	0·52
AVAILABLE INTERVENTION TIME (Secs)	2·12	2·12	2·12	2·12	2·12	2·12	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·22	0·46	0·5	0·48	0·48	0·46	0·52	0·5
FIRST RESPONSE (Secs)	1·76	2·3	2·04	1·46	1·66	1·7	1·98	0·9
Nr AT FIRST RESPONSE (%)	84·05	75·43	80·34	87·94	84·85	83·7	86·78	97·02
MIN Nr (%)	73·83	67·37	71·68	76·15	73·59	73·07	85·9	81·8
DELTA Nr (%)	10·22	8·06	8·66	11·79	11·26	10·63	0·88	15·22
TIME AT MIN COLLECTIVE (Secs)	2	2·54	2·34	1·76	2·46	2·12	2·64	1·76
TIME TO MIN COLLECTIVE (Secs)	0·24	0·24	0·3	0·3	0·8	0·42	0·66	0·86
ROTORCRAFT RESPONSE TIME (Secs)	1·22	0·46	0·5	0·48	0·48	0·46	0·52	0·5
PILOT RESPONSE TIME (Secs)	0·54	1·84	1·54	0·98	1·18	1·24	1·46	0·4
AVAILABLE INTERVENTION TIME (Secs)	1·56	1·56	1·56	1·56	1·56	1·56	5·4	1000

Appendix 6 (Continued)

PILOT 3

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·44	0·58	0·54	0·58	0·58	0·56	0·56	0·56
FIRST RESPONSE (Secs)	1·4	1·4	1·3	1·12	0·86	0·98	1·48	1·06
Nr AT FIRST RESPONSE (%)	92·31	92·3	92·82	95·23	98·05	96·7	91·88	95·55
MIN Nr (%)	82·3	83·71	82·01	85·96	87·78	86·3	87·97	86·38
DELTA Nr (%)	10·01	8·59	10·81	9·27	10·27	10·4	3·91	9·17
TIME AT MIN COLLECTIVE (Secs)	2·4	2·3	2·64	1·96	1·92	2·06	3·68	1·86
TIME TO MIN COLLECTIVE (Secs)	1	0·9	1·34	0·84	1·06	1·08	2·2	0·8
ROTORCRAFT RESPONSE TIME (Secs)	1·44	0·58	0·54	0·58	0·58	0·56	0·56	0·56
PILOT RESPONSE TIME (Secs)	−0·04	0·82	0·76	0·54	0·28	0·42	0·92	0·5
AVAILABLE INTERVENTION TIME (Secs)	1·98	1·98	1·98	1·98	1·98	1·98	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·24	0·48	0·5	0·5	0·48	0·5	0·48	0·48
FIRST RESPONSE (Secs)	1·88	2	2	2·14	1·98	2·18	1·9	0·86
Nr AT FIRST RESPONSE (%)	82·63	80·33	80·91	79·33	80·4	78·52	85·84	97·1
MIN Nr (%)	71·89	70·48	72·59	72·35	71·22	70·85	84·84	81·69
DELTA Nr (%)	10·74	9·85	8·32	6·98	9·18	7·67	1	15·41
TIME AT MIN COLLECTIVE (Secs)	3·02	2·92	2·7	2·62	2·58	2·88	3·5	1·74
TIME TO MIN COLLECTIVE (Secs)	1·14	0·92	0·7	0·48	0·6	0·7	1·6	0·88
ROTORCRAFT RESPONSE TIME (Secs)	1·24	0·48	0·5	0·5	0·48	0·5	0·48	0·48
PILOT RESPONSE TIME (Secs)	0·64	1·52	1·5	1·64	1·5	1·68	1·42	0·38
AVAILABLE INTERVENTION TIME (Secs)	1·65	1·65	1·65	1·65	1·65	1·65	5·4	1000

PILOT 4

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·42	0·58	0·54	0·56	0·56	0·56	0·56	0·56
FIRST RESPONSE (Secs)	0·94	0·86	0·92	1·08	1·12	1·24	0·56	0·9
Nr AT FIRST RESPONSE (%)	96·79	98·09	86·87	95·71	94·85	93·63	100·54	97·4
MIN Nr (%)	84·33	86·46	84·88	87·78	83·41	82·36	91·23	86·9
DELTA Nr (%)	12·46	11·63	1·99	7·93	11·44	11·27	9·31	10·5
TIME AT MIN COLLECTIVE (Secs)	2·5	1·98	2·08	1·8	2·4	3·08	1·46	2·78
TIME TO MIN COLLECTIVE (Secs)	1·56	1·12	1·16	0·72	1·28	1·84	0·9	1·88
ROTORCRAFT RESPONSE TIME (Secs)	1·42	0·58	0·54	0·56	0·56	0·56	0·56	0·56
PILOT RESPONSE TIME (Secs)	−0·48	0·28	0·38	0·52	0·56	0·68	0	0·34
AVAILABLE INTERVENTION TIME (Secs)	2·02	2·02	2·02	2·02	2·02	2·02	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·24	0·48	0·5	0·5	0·48	0·5	0·48	0·48
FIRST RESPONSE (Secs)	1·38	1·38	2·18	1·3	1·42	1·5	1·26	0·84
Nr AT FIRST RESPONSE (%)	89·88	89·37	78·33	90·95	88·75	88·24	91·84	97·1
MIN Nr (%)	76·34	77	69·76	79·31	72·65	75·65	86·17	83·77
DELTA Nr (%)	13·54	12·37	8·57	11·64	16·1	12·59	5·67	13·33
TIME AT MIN COLLECTIVE (Secs)	2·46	2·46	2·8	2·14	2·78	2·38	2·28	1·7
TIME TO MIN COLLECTIVE (Secs)	1·08	1·08	0·62	0·84	1·36	0·88	1·02	0·86
ROTORCRAFT RESPONSE TIME (Secs)	1·24	0·48	0·5	0·5	0·48	0·5	0·48	0·48
PILOT RESPONSE TIME (Secs)	0·14	0·9	1·68	0·8	0·94	1	0·78	0·36
AVAILABLE INTERVENTION TIME (Secs)	1·4	1·4	1·4	1·4	1·4	1·4	5·4	1000

Appendix 6 (Continued)

PILOT 5

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1.94	0.58	0.58	0.56	0.56	0.56	0.58	0.56
FIRST RESPONSE (Secs)	0.86	0.74	0.7	0.96	1.02	0.7	0.94	1.1
Nr AT FIRST RESPONSE (%)	97.53	99.09	99.41	96.84	96.16	99.32	97.45	95.34
MIN Nr (%)	89.74	91.74	91.52	88.59	88.08	90.74	90	85.56
DELTA Nr (%)	7.79	7.35	7.89	8.25	8.08	8.58	7.45	9.78
TIME AT MIN COLLECTIVE (Secs)	1.12	1.12	1.12	1.52	1.5	1.3	1.32	1.9
TIME TO MIN COLLECTIVE (Secs)	0.26	0.38	0.42	0.56	0.48	0.6	0.38	0.8
ROTORCRAFT RESPONSE TIME (Secs)	1.94	0.58	0.58	0.56	0.56	0.56	0.58	0.56
PILOT RESPONSE TIME (Secs)	−1.08	0.16	0.12	0.4	0.46	0.14	0.36	0.54
AVAILABLE INTERVENTION TIME (Secs)	2.18	2.18	2.18	2.18	2.18	2.18	30.8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1.46	0.48	0.48	0.48	0.48	0.48	0.48	0.5
FIRST RESPONSE (Secs)	0.94	1.1	1.02	1.34	1.46	1.16	1.2	0.86
Nr AT FIRST RESPONSE (%)	95.91	93.46	94.38	89.99	87.73	92.49	92.8	97.16
MIN Nr (%)	84.22	82.16	82.81	78.42	76.35	80.62	87.49	82.42
DELTA Nr (%)	11.69	11.3	11.57	11.57	11.38	11.87	5.31	14.74
TIME AT MIN COLLECTIVE (Secs)	1.2	1.4	1.46	1.6	1.72	1.56	1.68	1.72
TIME TO MIN COLLECTIVE (Secs)	0.26	0.3	0.44	0.26	0.26	0.4	0.48	0.86
ROTORCRAFT RESPONSE TIME (Secs)	1.46	0.48	0.48	0.48	0.48	0.48	0.48	0.5
PILOT RESPONSE TIME (Secs)	−0.52	0.62	0.54	0.86	0.98	0.68	0.72	0.36
AVAILABLE INTERVENTION TIME (Secs)	1.46	1.46	1.46	1.46	1.46	1.46	5.4	1000

PILOT 6

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1.48	0.58	0.56	0.58	0.58	0.58	0.58	0.58
FIRST RESPONSE (Secs)	1.98	1.42	1.14	1.4	1.42	1.08	1.16	1.12
Nr AT FIRST RESPONSE (%)	86.66	92.09	94.97	92.65	92.52	95.8	94.99	95.27
MIN Nr (%)	80.3	84.86	87.22	85.3	85.39	88.95	90.66	86.82
DELTA Nr (%)	6.36	7.23	7.75	7.35	7.13	6.85	4.33	8.45
TIME AT MIN COLLECTIVE (Secs)	2.6	1.96	1.58	2.06	2.14	1.3	1.78	1.66
TIME TO MIN COLLECTIVE (Secs)	0.62	0.54	0.44	0.66	0.72	0.22	0.62	0.54
ROTORCRAFT RESPONSE TIME (Secs)	1.48	0.58	0.56	0.58	0.58	0.58	0.58	0.58
PILOT RESPONSE TIME (Secs)	0.5	0.84	0.58	0.82	0.84	0.5	0.58	0.54
AVAILABLE INTERVENTION TIME (Secs)	2.27	2.27	2.27	2.27	2.27	2.27	30.8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1.24	0.5	0.5	0.5	0.5	0.5	0.56	0.5
FIRST RESPONSE (Secs)	2.12	1.7	1.68	1.68	1.82	1.88	2.46	0.88
Nr AT FIRST RESPONSE (%)	79.4	84.98	85.43	85.3	83.29	82.89	85.57	96.95
MIN Nr (%)	70.12	74.26	75.82	75.58	74.14	72.43	85	82.43
DELTA Nr (%)	9.28	10.72	9.61	9.72	9.15	10.46	0.57	14.52
TIME AT MIN COLLECTIVE (Secs)	2.92	2.2	2.06	2.06	2.12	2.22	3.28	1.92
TIME TO MIN COLLECTIVE (Secs)	0.8	0.5	0.38	0.38	0.3	0.34	0.82	1.04
ROTORCRAFT RESPONSE TIME (Secs)	1.24	0.5	0.5	0.5	0.5	0.5	0.56	0.5
PILOT RESPONSE TIME (Secs)	0.88	1.2	1.18	1.18	1.32	1.38	1.9	0.38
AVAILABLE INTERVENTION TIME (Secs)	1.52	1.52	1.52	1.52	1.52	1.52	5.4	1000

Appendix 6 (Continued)

PILOT 7

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·44	0·6	0·56	0·58	0·58	0·58	0·56	0·56
FIRST RESPONSE (Secs)	2·38	1·24	1·86	1·92	1·86	2·14	1·44	1·1
Nr AT FIRST RESPONSE (%)	82·84	94·67	86·87	87·21	87·61	84·46	92·08	95·44
MIN Nr (%)	76·99	85·02	77·06	80·6	79·56	78·22	87·78	86·31
DELTA Nr (%)	5·85	9·65	9·81	6·61	8·05	6·24	4·3	9·13
TIME AT MIN COLLECTIVE (Secs)	3·1	3·02	3·78	2·92	2·86	3	3·16	1·88
TIME TO MIN COLLECTIVE (Secs)	0·72	1·78	1·92	1	1	0·86	1·72	0·78
ROTORCRAFT RESPONSE TIME (Secs)	1·44	0·6	0·56	0·58	0·58	0·58	0·56	0·56
PILOT RESPONSE TIME (Secs)	0·94	0·64	1·3	1·34	1·28	1·56	0·88	0·54
AVAILABLE INTERVENTION TIME (Secs)	2·2	2·2	2·2	2·2	2·2	2·2	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·26	0·5	0·5	0·48	0·48	0·5	0·5	0·5
FIRST RESPONSE (Secs)	2·66	2·38	2·34	2·7	2·68	2·56	3·26	0·88
Nr AT FIRST RESPONSE (%)	73·53	76·91	76·56	72·25	72·21	75·15	85·54	79·02
MIN Nr (%)	68·57	70·27	67·73	67·03	65·05	68·51	81·84	82·4
DELTA Nr (%)	4·96	6·64	8·83	5·22	7·16	6·64	3·7	−3·38
TIME AT MIN COLLECTIVE (Secs)	3·12	2·86	3·24	3·46	3·56	3·18	4·28	1·82
TIME TO MIN COLLECTIVE (Secs)	0·46	0·48	0·9	0·76	0·88	0·62	1·02	0·94
ROTORCRAFT RESPONSE TIME (Secs)	1·26	0·5	0·5	0·48	0·48	0·5	0·5	0·5
PILOT RESPONSE TIME (Secs)	1·4	1·88	1·84	2·22	2·2	2·06	2·76	0·38
AVAILABLE INTERVENTION TIME (Secs)	1·8	1·8	1·8	1·8	1·8	1·8	5·4	1000

PILOT 8

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·46	0·56	0·56	0·56	0·54		0·6	0·58
FIRST RESPONSE (Secs)	1·88	0·88	1·68	0·86	1·08		1·3	1·14
Nr AT FIRST RESPONSE (%)	87·64	97·86	89·9	97·92	95·35	94·02	93·95	95·54
MIN Nr (%)	81·63	89·72	83·18	90·65	88·9	85·23	90·2	88·56
DELTA Nr (%)	6·01	8·14	6·72	7·27	6·45	8·79	3·75	6·98
TIME AT MIN COLLECTIVE (Secs)	2·68	1·78	2·5	1·54	1·56	2·7	1·78	1·82
TIME TO MIN COLLECTIVE (Secs)	0·8	0·9	0·82	0·68	0·48	2·7	0·48	0·68
ROTORCRAFT RESPONSE TIME (Secs)	1·46	0·56	0·56	0·56	0·54	0·53	0·6	0·58
PILOT RESPONSE TIME (Secs)	0·42	0·32	1·12	0·3	0·54	0·61	0·7	0·56
AVAILABLE INTERVENTION TIME (Secs)	2·42	2·42	2·42	2·42	2·42	2·42	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·18	0·48	0·48	0·52	0·48	0·48	0·48	0·48
FIRST RESPONSE (Secs)	1·78	1·94	1·62	1·96	1·96	2·04	1·9	0·84
Nr AT FIRST RESPONSE (%)	83·04	81·6	86·42	82·33	81·2	80·51	86·3	97·07
MIN Nr (%)	74·93	71·26	75·19	73·94	74·68	73·61	84·96	83·69
DELTA Nr (%)	8·11	10·34	11·23	8·39	6·52	6·9	1·34	13·38
TIME AT MIN COLLECTIVE (Secs)	2·36	2·78	2·18	2·52	2·46	2·52	2·66	1·82
TIME TO MIN COLLECTIVE (Secs)	0·58	0·84	0·56	0·56	0·5	0·48	0·76	0·98
ROTORCRAFT RESPONSE TIME (Secs)	1·18	0·48	0·48	0·52	0·48	0·48	0·48	0·48
PILOT RESPONSE TIME (Secs)	0·6	1·46	1·14	1·44	1·48	1·56	1·42	0·36
AVAILABLE INTERVENTION TIME (Secs)	1·66	1·66	1·66	1·66	1·66	1·66	5·4	1000

Appendix 6 (Continued)

PILOT 9

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·46	0·58	0·6	0·58	0·58	0·58	0·6	0·58
FIRST RESPONSE (Secs)	2·24	0·88	1·04	1·06	1·18	1·42	1·08	1·12
Nr AT FIRST RESPONSE (%)	84·24	97·8	96·68	96·27	94·77	92·7	96·41	95·54
MIN Nr (%)	77·06	84·16	86·76	83·54	84·53	82·96	90·29	86·73
DELTA Nr (%)	7·18	13·64	9·92	12·73	10·24	9·74	6·12	8·81
TIME AT MIN COLLECTIVE (Secs)	4·12	2·68	1·86	3·24	3·4	2·56	3·62	2·04
TIME TO MIN COLLECTIVE (Secs)	1·88	1·8	0·82	2·18	2·22	1·14	2·54	0·92
ROTORCRAFT RESPONSE TIME (Secs)	1·46	0·58	0·6	0·58	0·58	0·58	0·6	0·58
PILOT RESPONSE TIME (Secs)	0·78	0·3	0·44	0·48	0·6	0·84	0·48	0·54
AVAILABLE INTERVENTION TIME (Secs)	1·92	1·92	1·92	1·92	1·92	1·92	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·22	0·48	0·5	0·48	0·48	0·48	0·48	0·46
FIRST RESPONSE (Secs)	1·94	1·72	1·46	2·16	1·64	1·86	1·58	0·84
Nr AT FIRST RESPONSE (%)	81·74	84·48	88·24	77·76	85·52	83·18	88·25	97·02
MIN Nr (%)	71·49	73·21	74·3	69·21	71·23	75·09	85·54	82·73
DELTA Nr (%)	10·25	11·27	13·94	8·55	14·29	8·09	2·71	14·29
TIME AT MIN COLLECTIVE (Secs)	7	3·02	4·04	4·32	3·5	2·72	3	1·74
TIME TO MIN COLLECTIVE (Secs)	5·06	1·3	2·58	2·16	1·86	0·86	1·42	0·9
ROTORCRAFT RESPONSE TIME (Secs)	1·22	0·48	0·5	0·48	0·48	0·48	0·48	0·46
PILOT RESPONSE TIME (Secs)	0·72	1·24	0·96	1·68	1·16	1·38	1·1	0·38
AVAILABLE INTERVENTION TIME (Secs)	1·5	1·5	1·5	1·5	1·5	1·5	5·4	1000

PILOT 10

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·38	0·54	0·56	0·56	0·54	0·58	0·56	0·56
FIRST RESPONSE (Secs)	1·22	1·54	0·96	1·2	1·24	1·02	1·36	1·06
Nr AT FIRST RESPONSE (%)	93·7	89·97	96·81	94·11	93·19	96·43	92·79	95·72
MIN Nr (%)	81·61	81·57	85·77	84·67	83·09	84·96	88·29	86·7
DELTA Nr (%)	12·09	8·4	11·04	9·44	10·1	11·47	4·5	9·02
TIME AT MIN COLLECTIVE (Secs)	2·5	2·56	1·94	2·66	2·86	2·58	2·4	2·4
TIME TO MIN COLLECTIVE (Secs)	1·28	1·02	0·98	1·46	1·62	1·56	1·04	1·34
ROTORCRAFT RESPONSE TIME (Secs)	1·38	0·54	0·56	0·56	0·54	0·58	0·56	0·56
PILOT RESPONSE TIME (Secs)	–0·16	1	0·4	0·64	0·7	0·44	0·8	0·5
AVAILABLE INTERVENTION TIME (Secs)	1·93	1·93	1·93	1·93	1·93	1·93	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·18	0·48	0·5	0·5	0·48	0·46	0·48	0·48
FIRST RESPONSE (Secs)	1·82	1·8	2	1·66	2·4	1·92	1·78	0·84
Nr AT FIRST RESPONSE (%)	82·58	83·4	80·79	85·78	74·37	80·48	87·19	96·93
MIN Nr (%)	72·66	73·95	71·62	75·27	68·44	71·62	85·55	83·78
DELTA Nr (%)	9·92	9·45	9·17	10·51	5·93	8·86	1·64	13·15
TIME AT MIN COLLECTIVE (Secs)	2·82	2·86	2·86	2·86	3·24	2·82	2·48	1·8
TIME TO MIN COLLECTIVE (Secs)	1	1·06	0·86	1·2	0·84	0·9	0·7	0·96
ROTORCRAFT RESPONSE TIME (Secs)	1·18	0·48	0·5	0·5	0·48	0·46	0·48	0·48
PILOT RESPONSE TIME (Secs)	0·64	1·32	1·5	1·16	1·92	1·46	1·3	0·36
AVAILABLE INTERVENTION TIME (Secs)	1·64	1·64	1·64	1·64	1·64	1·64	5·4	1000

PILOT 11

ATTENTIVE FLIGHT

	BASELINE	BASE. + PRED.	MULTITONES	ENHANCED VISUAL	TONES + MESSAGES	MODULATED TONE	AUTO INTERVENTION 1	AUTO INTERVENTION 2
FIRST STIMULI (Secs)	1·46	0·58	0·58	0·58	0·58	0·58	0·58	0·58
FIRST RESPONSE (Secs)	1·2	0·86	1·16	1·16	1·32	1·36	1·18	1·04
Nr AT FIRST RESPONSE (%)	94·5	98·01	94·99	95·13	93·33	92·9	94·81	96·24
MIN Nr (%)	83·98	86·82	84·1	86·38	83·58	84·09	89·17	87·32
DELTA Nr (%)	10·52	11·19	10·89	8·75	9·75	8·81	5·64	8·92
TIME AT MIN COLLECTIVE (Secs)	2·1	2·36	2·42	1·92	2·16	2·08	2·42	1·8
TIME TO MIN COLLECTIVE (Secs)	0·9	1·5	1·26	0·76	0·84	0·72	1·24	0·76
ROTORCRAFT RESPONSE TIME (Secs)	1·46	0·58	0·58	0·58	0·58	0·58	0·58	0·58
PILOT RESPONSE TIME (Secs)	–0·26	0·28	0·58	0·58	0·74	0·78	0·6	0·46
AVAILABLE INTERVENTION TIME (Secs)	1·97	1·97	1·97	1·97	1·97	1·97	30·8	1000

PASSIVE FLIGHT

	BASELINE	BASE. + PRED.	MULTITONES	ENHANCED VISUAL	TONES + MESSAGES	MODULATED TONE	AUTO INTERVENTION 1	AUTO INTERVENTION 2
FIRST STIMULI (Secs)	1·22	0·48	0·5	0·48	0·48	0·48	0·48	0·5
FIRST RESPONSE (Secs)	2·06	1·78	1·68	1·86	1·88	1·7	2·36	0·86
Nr AT FIRST RESPONSE (%)	79·79	83·27	85·52	82·3	82·01	84·48	84·91	97·19
MIN Nr (%)	69·27	71·69	75·92	70·84	71·48	73·08	84·91	82·64
DELTA Nr (%)	10·52	11·58	9·6	11·46	10·53	11·4	0	14·55
TIME AT MIN COLLECTIVE (Secs)	4·32	2·8	2·46	3·22	2·64	2·46	3·36	1·76
TIME TO MIN COLLECTIVE (Secs)	2·26	1·02	0·78	1·36	0·76	0·76	1	0·9
ROTORCRAFT RESPONSE TIME (Secs)	1·22	0·48	0·5	0·48	0·48	0·48	0·48	0·5
PILOT RESPONSE TIME (Secs)	0·84	1·3	1·18	1·38	1·4	1·22	1·88	0·36
AVAILABLE INTERVENTION TIME (Secs)	1·51	1·51	1·51	1·51	1·51	1·51	5·4	1000

PILOT 12

ATTENTIVE FLIGHT

	BASELINE	BASE. + PRED.	MULTITONES	ENHANCED VISUAL	TONES + MESSAGES	MODULATED TONE	AUTO INTERVENTION 1	AUTO INTERVENTION 2
FIRST STIMULI (Secs)	1·54	0·58	0·6	0·58	0·56	0·58	0·56	0·56
FIRST RESPONSE (Secs)	2·42	1·14	1·82	0·88	0·72	0·76	1·12	1·12
Nr AT FIRST RESPONSE (%)	83·37	95·34	88·7	97·81	99·21	98·93	95·31	95·29
MIN Nr (%)	78·12	87·98	82·38	91·25	92·3	90·38	90·25	86·06
DELTA Nr (%)	5·25	7·36	6·32	6·56	6·91	8·55	5·06	9·23
TIME AT MIN COLLECTIVE (Secs)	2·78	1·44	2·18	1·24	0·94	1·34	1·68	1·68
TIME TO MIN COLLECTIVE (Secs)	0·36	0·3	0·36	0·36	0·22	0·58	0·56	0·56
ROTORCRAFT RESPONSE TIME (Secs)	1·54	0·58	0·6	0·58	0·56	0·58	0·56	0·56
PILOT RESPONSE TIME (Secs)	0·88	0·56	1·22	0·3	0·16	0·18	0·56	0·56
AVAILABLE INTERVENTION TIME (Secs)	2·3	2·3	2·3	2·3	2·3	2·3	30·8	1000

PASSIVE FLIGHT

	BASELINE	BASE. + PRED.	MULTITONES	ENHANCED VISUAL	TONES + MESSAGES	MODULATED TONE	AUTO INTERVENTION 1	AUTO INTERVENTION 2
FIRST STIMULI (Secs)	1·24	0·5	0·5	0·5	0·5	0·5	0·5	0·5
FIRST RESPONSE (Secs)	2·3	1·34	1·66	1·62	1·9	1·68	1·34	0·9
Nr AT FIRST RESPONSE (%)	77·06	90·75	86·01	86·79	82·71	85·96	91·3	96·99
MIN Nr (%)	68·69	80·18	77·56	76·62	72·39	77·26	85·97	82·13
DELTA Nr (%)	8·37	10·57	8·45	10·17	10·32	8·7	5·33	14·86
TIME AT MIN COLLECTIVE (Secs)	2·78	1·72	2·12	2·46	2·4	2·46	2·46	1·84
TIME TO MIN COLLECTIVE (Secs)	0·48	0·38	0·46	0·84	0·5	0·78	1·12	0·94
ROTORCRAFT RESPONSE TIME (Secs)	1·24	0·5	0·5	0·5	0·5	0·5	0·5	0·5
PILOT RESPONSE TIME (Secs)	1·06	0·84	1·16	1·12	1·4	1·18	0·84	0·4
AVAILABLE INTERVENTION TIME (Secs)	1·6	1·6	1·6	1·6	1·6	1·6	5·4	1000

PILOT 13

ATTENTIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·4	0·58	0·54	0·58	0·56	0·56	0·56	0·58
FIRST RESPONSE (Secs)	1·9	1·62	2·1	1·92	1·32	1·16	1·88	1·12
Nr AT FIRST RESPONSE (%)	86·33	90·05	83·54	86·99	93·15	94·6	88·86	95·36
MIN Nr (%)	77·46	82·2	76·2	79·06	80·6	82·83	87·3	85·63
DELTA Nr (%)	8·87	7·85	7·34	7·93	12·55	11·77	1·56	9·73
TIME AT MIN COLLECTIVE (Secs)	3·02	2·56	3·08	2·86	2·86	2·36	2·92	1·94
TIME TO MIN COLLECTIVE (Secs)	1·12	0·94	0·98	0·94	1·54	1·2	1·04	0·82
ROTORCRAFT RESPONSE TIME (Secs)	1·4	0·58	0·54	0·58	0·56	0·56	0·56	0·58
PILOT RESPONSE TIME (Secs)	0·5	1·04	1·56	1·34	0·76	0·6	1·32	0·54
AVAILABLE INTERVENTION TIME (Secs)	2·03	2·03	2·03	2·03	2·03	2·03	30·8	1000

PASSIVE FLIGHT

	BASELINE	*BASE. + PRED.*	*MULTITONES*	*ENHANCED VISUAL*	*TONES + MESSAGES*	*MODULATED TONE*	*AUTO INTERVENTION 1*	*AUTO INTERVENTION 2*
FIRST STIMULI (Secs)	1·22	0·48	0·48	0·48	0·5	0·5	0·48	0·5
FIRST RESPONSE (Secs)	2·96	2·38	2·72	2·2	2·52	2·56	3·1	0·88
Nr AT FIRST RESPONSE (%)	69·54	75·55	71·53	77·78	74·87	73·94	84·93	97·04
MIN Nr (%)	65·02	67·19	66·65	69·83	67·67	66·21	81·66	82·12
DELTA Nr (%)	4·52	8·36	4·88	7·95	7·2	7·73	3·27	14·92
TIME AT MIN COLLECTIVE (Secs)	4·04	3·4	3·62	3·12	3·32	3·34	4·04	1·78
TIME TO MIN COLLECTIVE (Secs)	1·08	1·02	0·9	0·92	0·8	0·78	0·94	0·9
ROTORCRAFT RESPONSE TIME (Secs)	1·22	0·48	0·48	0·48	0·5	0·5	0·48	0·5
PILOT RESPONSE TIME (Secs)	1·74	1·9	2·24	1·72	2·02	2·06	2·62	0·38
AVAILABLE INTERVENTION TIME (Secs)	1·79	1·79	1·79	1·79	1·79	1·79	5·4	1000

Appendix 7 2X8 Repeated Measures Anova

MINIMUM Nr DATA

SUBJECT No.	ATTENTIVE FLIGHT								PASSIVE FLIGHT								Sum of Rows	Squared
	BASE	PRED	MULT	ENV	T+M	MOD	AUTO 1	AUTO 2	BASE	PRED	MULT	ENV	T+M	MOD	AUTO 1	AUTO 2		
1	83·90	86·35	86·59	88·20	86·61	86·07	90·95	86·65	74·14	78·9	73·82	76·52	76·63	72·86	87·15	83·39	1318·73	1739049
2	88·21	92·92	88·25	87·91	86·96	84·87	88·77	87·16	73·83	67·37	71·68	76·15	73·59	73·07	85·9	81·8	1308·44	1712015
3	82·30	83·71	82·01	85·96	87·78	86·30	87·97	86·38	71·89	70·48	72·59	72·35	71·22	70·85	84·84	81·69	1278·32	1634102
4	84·33	86·46	84·88	87·78	83·41	82·36	91·23	86·90	76·34	77	69·76	79·31	72·65	75·65	86·17	83·77	1308	1710864
5	89·74	91·74	91·52	88·59	88·08	90·74	90·00	85·56	84·22	82·16	82·81	78·42	76·35	80·62	87·49	82·42	1370·46	1878161
6	80·30	84·86	87·22	85·30	85·39	88·95	90·66	86·82	70·12	74·26	75·82	75·58	74·14	72·43	85	82·43	1299·28	1688129
7	76·99	85·02	77·06	80·60	79·56	78·22	87·78	86·31	68·57	70·27	67·73	67·03	65·05	68·51	81·84	82·4	1222·94	1495582
8	81·63	89·72	83·18	90·65	88·90	85·23	90·20	88·56	74·93	71·26	75·19	73·94	74·68	73·61	84·96	83·69	1310·33	1716965
9	77·06	84·16	86·76	83·54	84·53	82·96	90·29	86·73	71·49	73·21	74·3	69·21	71·23	75·09	85·54	82·73	1278·83	1635406
10	81·61	81·57	85·77	84·67	83·09	84·96	88·29	86·70	72·66	73·95	71·62	75·27	68·44	71·62	85·55	83·78	1279·55	1637248
11	83·98	86·82	84·10	86·38	83·58	84·09	89·17	87·32	69·27	71·69	75·92	70·84	71·48	73·08	84·91	82·64	1285·27	1651919
12	78·12	87·98	82·38	91·25	92·30	90·38	90·25	86·06	68·69	80·18	77·56	76·62	72·39	77·26	85·97	82·13	1319·52	1741133
13	77·46	82·20	76·20	79·06	80·60	82·83	87·30	85·63	65·02	67·19	66·65	69·83	67·67	66·21	81·66	82·12	1217·63	1482623
Sum of Columns	1065·63	1123·51	1095·92	1119·89	1110·79	1107·96	1162·86	1126·78	941·17	957·92	955·45	961·07	935·52	950·86	1106·98	1074·99	16797·3	21723195
Means	81·972	86·424	84·302	86·145	85·445	85·228	89·451	86·675	72·398	73·686	73·496	73·928	71·963	73·143	85·152	82·692		

SOURCE	df	SS	MS	F	Crit. Value (at p<0.001)		Sig
Attention Level	1	5094·342	5094·342	772·1981	18·64	(1,12)	<0·001
Strategy	7	2136·105	305·1579	39·45476	4·09	(7,84)	<0·001
Subjects	12	1212·751	101·0626	24·1306	3·32	(12,84)	<0·001
Attention Level X Strategy	7	639·1468	91·30668	21·8012	4·09	(7,84)	<0·001
Attention Level X Subjects	12	79·16635	6·597196				
Strategy X Subject	84	649·6875	7·734375				
Attention Level X Strategy X Subject	84	351·8046	4·18815				
TOTAL	207	10163					
(correction factor =	1356487)						

ACTUAL INTERVENTION TIME DATA

SUBJECT No.	ATTENTIVE FLIGHT								PASSIVE FLIGHT								Sum of Rows	Squared
	BASE	PRED	MULT	ENV	T+M	MOD	AUTO 1	AUTO 2	BASE	PRED	MULT	ENV	T+M	MOD	AUTO 1	AUTO 2		
1	1·22	1·06	1·18	0·86	1·1	1·08	0·9	1·12	1·62	1·46	1·78	1·78	1·64	2·02	1·3	0·8	20·92	437·6464
2	0·9	0·62	0·9	1·02	1·08	1·2	1·16	1·08	1·76	2·3	2·04	1·46	1·66	1·7	1·98	0·9	21·76	473·4976
3	1·4	1·4	1·3	1·12	0·86	0·98	1·48	1·06	1·88	2	2	2·14	1·98	2·18	1·9	0·86	24·54	602·2116
4	0·94	0·86	0·92	1·08	1·12	1·24	0·56	0·9	1·38	1·38	2·18	1·3	1·42	1·5	1·26	0·84	18·88	356·4544
5	0·86	0·74	0·7	0·96	1·02	0·7	0·94	1·1	0·94	1·1	1·02	1·34	1·46	1·16	1·2	0·86	16·1	259·21
6	1·98	1·42	1·14	1·4	1·42	1·08	1·16	1·12	2·12	1·7	1·68	1·68	1·82	1·88	2·46	0·88	24·94	622·0036
7	2·38	1·24	1·86	1·92	1·86	2·14	1·44	1·1	2·66	2·38	2·34	2·7	2·68	2·56	3·26	0·88	33·4	1115·56
8	1·88	0·88	1·68	0·86	1·08	1·18	1·3	1·14	1·78	1·94	1·62	1·96	1·96	2·04	1·9	0·84	24·04	577·8415
9	2·24	0·88	1·04	1·06	1·18	1·42	1·08	1·12	1·94	1·72	1·46	2·16	1·64	1·86	1·58	0·84	23·22	539·1684
10	1·22	1·54	0·96	1·2	1·24	1·02	1·36	1·06	1·82	1·8	2	1·66	2·4	1·92	1·78	0·84	23·82	567·3924
11	1·2	0·86	1·16	1·16	1·32	1·36	1·18	1·04	2·06	1·78	1·68	1·86	1·88	1·7	2·36	0·86	23·46	550·3716
12	2·42	1·14	1·82	0·88	0·72	0·76	1·12	1·12	2·3	1·34	1·66	1·62	1·9	1·68	1·34	0·9	22·72	516·1984
13	1·9	1·62	2·1	1·92	1·32	1·16	1·88	1·12	2·96	2·38	2·72	2·2	2·52	2·56	3·1	0·88	32·34	1045·876
Sum of Columns	20·54	14·26	16·76	15·44	15·32	15·32	15·56	14·08	25·22	23·28	24·18	23·86	24·96	24·76	25·42	11·18	310·1383	7663·431
Means	1·580	1·097	1·289	1·188	1·178	1·178	1·197	1·083	1·940	1·791	1·860	1·835	1·920	1·905	1·955	0·860		

SOURCE	df	SS	MS	F	Crit. Value (at $p<0.001$)		Sig
Attention Level	1	14·85251	14·85251	147·3087	18·64	(1,12)	<0·001
Strategy	7	9·490722	1·355817	7·518007	4·09	(7,84)	<0·001
Subjects	12	16·5328	1·377734	21·27804	3·32	(12,84)	<0·001
Attention Level X Strategy	7	5·029025	0·718432	11·09564	4·09	(7,84)	<0·001
Attention Level X Subjects	12	1·209909	0·100826				
Strategy X Subject	84	15·14878	0·180343				
Attention Level X Strategy X Subject	84	5·438923	0·064749				
TOTAL	207	60·55834					
(correction factor =	462·4317)						

Appendix 8 Example Questionnaire and Results

PRELIMINARY PILOT QUESTIONNAIRE

Please answer the following questions and bring the questionnaire with you to the trial. The information supplied will be treated in strictest confidence and will be used only for the purposes of this experiment. If there is insufficient room to answer the questions please use the space at the end of the questionnaire and clearly mark the answer with the question number to which it belongs. Thank you.

1. NAME:

2. AGE:

3. OCCUPATION AND POSITION:

4. TYPE OF HELICOPTER LICENCE HEL

5. EXPERIENCE

HELICOPTER TYPES FLOWN	HOURS

TOTAL HOURS (INC. FIXED WING) =

6. AVERAGE TOTAL HELICOPTER HOURS PER YEAR =

7. CURRENT TYPES FLOWN

8. HAVE YOU EVER EXPERIENCED AN ENGINE FAILURE IN FLIGHT

(a) **TWIN** SINGLE ENGINE FAILURE **YES/NO**

DOUBLE ENGINE FAILURE **YES/NO**

(b) **SINGLE** **YES/NO**

IF YES TO ANY OF THE ABOVE PLEASE GIVE BRIEF DETAILS

9. (a) HAVE YOU HAD ANY PREVIOUS EXPERIENCE OF HELICOPTER SIMULATORS?

YES/NO

(b) IF YES PLEASE GIVE BRIEF DETAILS IN THE TABLE BELOW

AIRCRAFT TYPE	VISUAL SYSTEM	MOTION SYSTEM	HOURS FLOWN
	YES/NO	YES/NO	
	YES/NO	YES/NO	
	YES/NO	YES/NO	

(c) HAVE YOU EVER SUFFERED FROM SIMULATOR SICKNESS?

YES/NO

(d) IF YOU ANSWERED YES TO QUESTION 9(a) HAS YOUR SIMULATOR EXPERIENCE INCLUDED SIMULATED ENGINE FAILURES?

YES/NO

IF YES PLEASE GIVE BRIEF DETAILS

10. HOW ADEQUATE DO YOU CONSIDER THE CURRENT LOW ROTOR SPEED WARNING SYSTEMS WITH WHICH YOU ARE FAMILIAR?

UNSATISFACTORY IDEAL

1 2 3 4 5

END OF SORTIE QUESTIONNAIRE

Pilot .... Warning Strategy .... Sortie No. ....

Attentive Flight

1. Please give an overall rating for the rotor speed loss warning strategy seen in this sortie under attentive flight conditions

   Very poor   Excellent

   1 2 3 4 5 6 7

   Comments ....

2. What was the first indication that you were aware of that indicated you had a problem?

   ....

3. Was low Nr immediately and uniquely identifiable from the first warning?

   YES/NO

   If No please explain how you diagnosed the low Nr condition?

   ....

Passive Flight

4. Please give an overall rating for the rotor speed loss warning strategy seen in this sortie under passive flight conditions

   Very poor   Excellent

   1 2 3 4 5 6 7

5. What was the first indication that you were aware of that indicated you had a problem?

   ....

6. Was low Nr immediately and uniquely identifiable from the first warning?

   YES/NO

   If No please explain how you diagnosed the low Nr condition?

   ....

General

7. At any time did you find features of the low rotor speed warning strategy intrusive annoying or distracting?

YES/NO

If yes, which features were annoying and why?

....

8. Please rate the strategy for aiding rotor speed control in autorotative flight

Very poor Excellent

1 2 3 4 5 6 7

Comments ....

9. At any time during the sortie were you aware of any discrepancies between the displays and the rotor speed warning strategy?

YES/NO

If yes please describe the nature of the discrepancy.

....

10. At any time during the sortie was there any confusion associated with the low rotor speed warning?

YES/NO

If YES please describe the nature of this confusion

....

11. If the low rotor warning strategy contained a voice component please rate your level of satisfaction with the voice component.

Very poor Excellent

1 2 3 4 5 6 7

If you rated less than 7 on question 11 please give your ideal specification for the voice component of a low rotor warning strategy.

....

12. Please give an overall rating for the rotor speed warning strategy seen in this sortie under both attentive and passive flight conditions.

Very poor Excellent

1 2 3 4 5 6 7

Comments ....

13. Do you feel the strategy seen in this sortie could be improved in any way?

YES/NO

If yes please describe your recommendations below:

FINAL QUESTIONNAIRE

Pilot ....

Section A: Simulation

1. How realistic would you rate the simulation?

   Not at all   Extremely Realistic

   1   2   3   4   5

2. How appropriate were the tasks for the evaluation of the rotor speed strategies?

   Not at all   Extremely

   1   2   3   4   5

3. Did you feel that the simulator impaired your performance in any way?

   YES/NO

   If YES, how?

   ....

Section B: Overall Preferences

1. Having completed all the sorties, please indicate your order of preference for the warning strategies presented during this trial.(1 = best, 8 = worst).

STRATEGY	RANK
1. Baseline	
2. Baseline + Prediction Filter	
3. Multi Tones	
4. Enhanced Visual	
5. Tones + Messages	
6. Modulated Tone	
7. Automated Intervention (1)	
8. Automated Intervention (2)	

2. Given a completely free choice please describe your ideal low rotor speed warning system. You may use elements of the systems you have seen here and or suggest any improvements which you think should be made.

Audio: ....
....
....
....

Visual: ....
....
....
....

Tactile: ....
....
....
....

Others: ....
....
....
....

THANK YOU FOR YOUR PARTICIPATION

Appendix 8 Questionnaire Results

Question 1 PLEASE GIVE AN OVERALL RATING FOR THE ROTOR SPEED LOSS WARNING STRATEGY SEEN UNDER ATTENTIVE FLIGHT CONDITIONS

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	MEAN	STD DEV	MEDIAN
Baseline	2	3	4	4	4	3	7	5	5	5	2	5	5	4·15	1·41	4·00
Baseline+Prediction	5	3	4	4	4	5	6	6	6	5	4	7	6	5·00	1·15	5·00
Multitones	4	4	4	3	4	6	7	5	7	4	4	7	6	5·00	1·41	4·00
Tones+Messages	4	4	4	5	4	5	6	5	6	3	5	6	6	4·85	0·99	5·00
Enhanced Visual	6	4	5	6	4	5	7	5	6	4	5	7	5	5·31	1·03	5·00
Modulated Tone	5	6	5	5	4	7	7	5	6	4	6	5	6	5·46	0·97	5·00
Auto 1	5	6	4	6	4	7	7	5	5	2	5	5	6	5·15	1·34	5·00
Auto 2	6	7	4	4	6	6	7	7	5	6	5	6	7	5·85	1·07	6·00

Question 2 WHAT WAS THE FIRST INDICATION THAT YOU WERE AWARE OF THAT INDICATED THAT YOU HAD A PROBLEM?

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13
Baseline	LOW Nr WARNING	HORN	Nr DROPPING ON STRIP DISPLAY	Nr GAUGE DECREASE	INDICATION	SAW Tq STRIP GOING DOWN	Ng/Nr VISUAL	YAW	AUDIO	R RPM INDICATION GOING LOW AS AUDIO CAME IN	GAUGES	LOW ROTOR AUDIO	LOW Nr AUDIO
Baseline+Prediction	Nr LOW TONE	STRIP GAUGE	LOW Nr AURAL WARNING	AUDIO	DON'T KNOW	AUDIO	Ng/Nr VISUAL	AUDIO	STRIPS THEN AUDIO	AUDIO ATTENSON	TORQUE LOSS	AUDIO	VISUAL CUES FROM INSTRUMENTS
Multitones	LOW Nr WARNING	STRIP GAUGE	LOW Nr AURAL WARNING	Nr DECAY	VISUAL (BUT I WAS BEING MORE ATTENTIVE THAN USUAL)	TONE	Ng/Nr (PERIPHERAL VISION)	AUDIO	MOVEMENT OF STRIP GAUGE	AUDIO	GAUGES MOVING RAPIDLY THEN TONE	TONE	VISUAL CUES FROM INSTRUMENTS
Tones+Messages	LOW Nr WARNING	VOICE WARNING	LOSS OF Nr ON TRIPLE TACHO STRIP DISPLAY	Nr GAUGE DECAY	DON'T KNOW, I THINK I SAW THE Nr FALL	SAW Tq STRIP MOVING DOWN	Ng DECREASING FOLLOWED BY Nr VIEWED THROUGH PERIPHERAL VISION	AUDIO	STRIP MOVEMENT	Nr STRIP GAUGE	TORQUE GAUGE DECREASING	I HAPPENED TO BE LOOKING AT THE Nr STRIP	LOW Nr AUDIO
Enhanced Visual	VISUAL INDICATOR	HORN	LOW Nr AURAL WARNING	AUDIO & ARROW	DON'T KNOW (AS PER EARLIER COMMENT)	LIGHT	AUDIO	AUDIO	AUDIO AND ENHANCED VISUAL ARROW	Nr STRIP AND AUDIO	TONE AND LIGHT TOGETHER, LIGHT PERHAPS DISTINGUISHING Nr TONE FROM OTHERS?	COMBINED LIGHT/AUDIO/ VISUAL SCAN	GENERAL VIS CUE FROM INSTRUMENTS
Modulated Tone	LOW Nr TONE	HORN/STRIP GAUGE	MOVEMENT ON Nr STRIP DISPLAY	LOW RPM GAUGE DROP	I THINK VISUAL ON THE STRIP. HOWEVER WHO KNOWS?	TONE/STRIP MOVEMENT	Ng/Nr PERIPHERAL VISION	AUDIO	MOVEMENT OF R ON STRIP	Nr STRIP AND AUDIO ATTENSON	SOUND OF TONE	COMBINATION OF AUDIO AND INSTRUMENTS	VISUAL GAUGE INDICATIONS
Auto 1	Nr LOW TONE	STRIP GAUGE AND HORN TOGETHER	LOW Nr WARNING (AURAL)	GAUGE THEN AUDIO	DON'T KNOW (POSSIBLY SEEING Nr DECAY, POSSIBLY AUDIO)	COMBINATION OF A/C PITCH CHANGE & STRIP MOVEMENT	Ng/Nr	AUDIO	STRIPS MOVING	SAW Nr DECAY TOGETHER WITH AUDIO	HORN	TONE/ INSTRUMENT INDICATIONS	AUDIO/LOSS OF TQ INDICATION
Auto 2	COLLECTIVE STARTED TO GO DOWN	STRIP GAUGE	DECREASE OF Nr ON STRIP INDICATOR	Nr DECAY	AUDIO PRIOR TO LEVER GOING DOWN	SIMULTANEOUS MOVEMENT OF STRIP/TONE		AUDIO	STRIPS MOVING	Nr STRIP AND AUDIO ATTENSON	TONE	AUDIO TONE/ INSTRUMENT SECOND	LOW Nr TONE

	TOTALS					
	AUDIO	GAUGES	ENV	AUD/VIS	OTHERS	DON'T KNOW
Baseline	5	7	0	0	1	0
Baseline+Prediction	7	5	0	0	0	1
Multitones	6	7	0	0	0	0
Tones+Messages	4	8	0	0	0	1
Enhanced Visual	4	1	2	5	0	1
Modulated Tone	3	6	0	4	0	0
Auto 1	4	3	0	4	1	1
Auto 2	4	4	0	3	1	1

Question 3 WAS LOW Nr IMMEDIATELY AND UNIQUELY IDENTIFIABLE FROM THE FIRST WARNING? IF NO PLEASE EXPLAIN HOW YOU DIAGNOSED THE LOW Nr CONDITION?

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	TOTALS YES	NO	DON'T KNOW
Baseline	YES	YES	YES	YES	YES	NO	YES	YES	NO	YES	YES	YES	YES	11	2	0
Baseline+Prediction	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	NO	11	2	0
Multitones	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES	NO	11	2	0
Tones+Messages	YES	YES	YES	YES	YES	NO	YES	YES	NO	NO	YES	YES	YES	10	3	0
Enhanced Visual	YES	YES	YES	YES	DON'T KNOW	NO	YES	YES	YES	YES	YES	DON'T KNOW	NO	9	2	2
Modulated Tone	YES	NO	YES	YES	DON'T KNOW	YES	YES	YES	YES	YES	YES		NO	9	2	2
Auto 1	YES	NO	YES	YES	?	NO (AUDIO TONE CONFIRMED)	YES	NO (VISUAL Nr GAUGE)	NO (NOT UNTIL THE AUDIO SOUNDED. IT IS NOT EASY TO SEE THE Nr STRIP MOVING BECAUSE THE OTHERS ARE MOVING)	YES	YES	YES	YES	8	4	1
Auto 2	NO (BY LOOKING AT THE GAUGE)	YES	YES	YES	?	YES	YES	YES	NO (PREVIOUS COMMENTS AUDIO WAS UNAMBIGUOUS)		YES	YES	YES	9	2	2

Question 4 PLEASE GIVE AN OVERALL RATING FOR THE ROTOR SPEED LOSS WARNING STRATEGY SEEN UNDER PASSIVE FLIGHT CONDITIONS

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	TOTALS MEAN	STD DEV	MEDIAN
Baseline	2	3	3	4	4	2	7	5	5	5	2	6	5	4·08	1·61	4
Baseline+Prediction	5	3	3	3	4	5	6	5	6	5	5	7	6	4·85	1·28	5
Multitones	3	5	4	3	4	4	7	5	7	5	4	6	6	4·85	1·34	5
Tones+Messages	4	4	3	5	4	6	6	5	6	3	5	6	6	4·85	1·14	5
Enhanced Visual	6	4	5	6	4	3	6	5	6	4	5	7	5	5·08	1·12	5
Modulated Tone	4	3	5	6	4	7	6	5	7	4	6	5	6	5·23	1·24	5
Auto 1	6	6	6	6	4	5	7	5	5	3	6	6	6	5·46	1·05	6
Auto 2	3	7	6	4	6	6	7	7	5	6	6	7	7	5·92	1·26	6

Question 5 WHAT WAS THE FIRST INDICATION THAT YOU WERE AWARE OF THAT INDICATED THAT YOU HAD A PROBLEM?

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	TOTALS AUDIO	GAUGES	ENV	AUD/VIS	OTHERS	DON'T KNOW
Baseline	NOISE TONE	HORN	POSSIBLY NOTICED Nr STRIP DISPLAY DECAYING IN PERIPHERAL VISION	AUDIO BACKED UP BY VISUAL GAUGE	DON'T KNOW	A MOVEMENT OF AN UNKNOWN TYPE ON THE GAUGES		AUDIO	STRIP GAUGES FALLING	JUST SAW ROTOR START TO DECAY	TORQUE GAUGE DROPPING – SEEN IN PERIPHERY	INSTRUMENT DISPLAY/Nr MOVING	LOW Nr AUDIO	4·00	6	0	2	0	1
Baseline+Prediction	Nr LOW TONE	HORN	LOW Nr AURAL WARNING	AUDIO	DON'T KNOW	COMBINATION – VISUAL THEN AUDIO CONFIRMED	VISUAL/AUDIO	AUDIO	AUDIO	AUDIO ATTENSON	TONE	AUDIO TONE	Nr AUDIO/ INSTRUMENT VISUAL CUES	10·00	0	0	2	0	1
Multitones	LOW Nr WARNING	HORN	LOW Nr AURAL WARNING	AUDIO	DON'T KNOW (HI Nr DID WARN ME OF THE HI Nr)	TONE	AUDIO	AUDIO	AUDIO	AUDIO WARNING	TONE	TONE	LOW Nr AUDIO	11·00	1	0	0	0	1
Tones+Messages	LOW Nr WARNING TONE	HORN	LOW Nr AURAL WARNING	Nr GAUGE AND AUDIO	DON'T KNOW	LOW Nr TONE	NG DECREASING FOLLOWED BY Nr		STRIPS AND AUDIO (TOGETHER?)	AUDIO ATTENSON	TONE+MESSAGE	AUDIO TONE	LOW Nr AUDIO	9·00	0	0	2	0	2
Enhanced Visual	LOW Nr WARNING	HORN	LOW Nr AURAL WARNING	AUDIO WARNING AND ARROW INDICATOR	DON'T KNOW	FLASHING LIGHT	AUDIO	AUDIO	AUDIO & DOWN ARROW	AUDIO ATTENSON AGAIN	TONE	LIGHT/SOUND TOGETHER		7·00	0	1	3	0	2
Modulated Tone	LOW Nr TONE	GAUGES MOVING	LOW Nr WARNING (AURAL)	L RPM HORN	AUDIO PERHAPS	TONE/TQ MOVEMENT	AUDIO	AUDIO	AUDIO	AUDIO ATTENSON	SOUND OF TONE	AUDIO TONE	VISUAL GAUGE INDICATIONS	9·00	2	0	1	0	1
Auto 1	Nr LOW TONE	Nr HORN	LOW Nr AURAL WARNING	AUDIO AND VISUAL	DON'T KNOW	TONE		AUDIO	AUDIO AND STRIPS	AUDIO WARNING	HORN	AUDIO TONE	LOW RPM AUDIO	9·00	0	0	2	0	2
Auto 2	Nr LOW TONE	HORN AND COLLECTIVE MOVING	LOW Nr AURAL WARNING	AUDIO	AUDIO	AUDIO		AUDIO AND COLLECTIVE LOWERED	AUDIO	AUDIO ATTENSON	TONE (+Nr GAUGE)	AUDIO TONE	LOW Nr TONE	9·00	0	0	1	2	1

Question 6 WAS LOW Nr IMMEDIATELY AND UNIQUELY IDENTIFIABLE FROM THE FIRST WARNING? IF NO PLEASE EXPLAIN HOW YOU DIAGNOSED THE LOW Nr CONDITION?

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	TOTALS YES	NO	DON'T KNOW	N/A
Baseline	YES	YES	YES	YES	YES	NO (AUDIO TONE AND LOOK AT STRIP GAUGE)	YES	YES	NOT UNTIL THE AUDIO	YES	YES	NO (COMBINATION OF INPUTS)	YES	10	3	0	0
Baseline+Prediction	YES	YES	YES	WHO KNOWS?	YES	NO (CONFIRMATION FROM AUDIO)	YES	YES	YES	YES	YES	YES	YES	11	1	1	0
Multitones	YES	YES	YES	NO (Nr GAUGE CHECKED – CONFUSION ON AUDIO TONES)	YES	NO (MOVING OF STRIPS CONFIRMED THE TONE)	YES	YES	YES	YES	PERHAPS (FROM FALLING GAUGES)	YES	YES	10	2	1	0
Tones+Messages	YES	YES	YES		NO	YES (ALTHOUGH UNIQUE-VOICE WARNING CLARIFIED IT IMMEDIATELY)	YES	YES	YES	(I THINK I RECOGNISED THE WARNING, BUT I CERTAINLY DID NOT REACT AS QUICKLY)	YES	YES	YES	10	1	1	1
Enhanced Visual	YES	YES (ARROWS CONFIRMED STRIP GAUGE)			DON'T KNOW	NO (AUDIO CONFIRMED)	YES	YES	YES	YES	PERHAPS (CERTAINLY THE LIGHT HELPS IN THE DIAGNOSIS)	YES	YES	8	1	2	2
Modulated Tone	YES	NO (STRIP GAUGE THEN THE HORN)			?	YES	YES	YES	YES	YES	YES	YES	NO (LOW Nr AUDIO)	8	2	1	2
Auto 1	YES	YES (WHEN COMPARED TO STRIP GAUGES)	YES	YES	WHO KNOWS I DON'T	YES	YES	NO (VISUAL Nr GAUGE)	YES	YES	NO (GAUGES AND HORN)	YES	YES	10	2	1	0
Auto 2	YES	YES	YES	YES	?	YES	YES	YES	YES	YES	NO (HAD TO LOOK AT Nr GAUGE	YES	YES	11	1	1	0

Question 7 AT ANY TIME DID YOU FIND FEATURES OF THE LOW ROTOR SPEED WARNING STRATEGY INTRUSIVE. ANNOYING OR DISTRACTING?

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	TOTALS YES	NO	DON'T KNOW
Baseline	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES (GOOD AS ATTENSON BUT IRRITATING IN DESCENT)	NO	NO	NO	1	12	0
Baseline+Prediction	NO	NO	NO	NO	NO	YES (LOUD AND HELD LOUD EVEN WITH Nr IN THE AMBER)	NO	NO	NO	NO	NO	NO	NO	1	12	0
Multitones	NO	NO	NO	NO	NO	YES (TONE DISTRACTING IN AUTOROTATION)	NO	NO	YES (FOR HIGH Nr IN THE TURN INTO WIND)	YES (AS COMMENT FOR BASELINE)	NO	NO	NO	3	10	0
Tones+Messages	YES (INITIAL VOICE OK, REPEATS DISTRACTING)	YES (FAILS TO IDENTIFY HIGH OR LOW Nr)	NO	NO	NO	NO (POSSIBLY COULD BE IF Nr IN AUTO MORE VARIABLE)	NO	NO	NO (BUT HI Nr TONES (NON-MODULATED) WERE)	NO	NO	NO	NO	2	11	0
Enhanced Visual	NO	NO	NO	NO	YES (DISLIKE 'THE ARROWS')	YES (LOUDNESS OF AUDIO AT NON CRITICAL Nr)	NO	NO	NO (BUT HI AUDIO WARNING WAS)	YES (LIGHT COMING ON IS DISTRACTING – ESPECIALLY DURING FLARE)	NO	NO	YES (HIGH Nr LIGHT)	4	9	0
Modulated Tone	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13	0
Auto 1	NO	NO	NO	YES	NO	NO	NO	NO	NO (BUT THE HIGH WARNING IS)	YES (UNLIKED – PERHAPS DUE TO MY INSTINCTIVE REACTIONS)	NO	NO	NO	2	11	0
Auto 2	NO	NO	NO	YES (AUTOMATIC COLLECTIVE LOWERING WAS CONFUSING – WHEN DO I TAKE OVER?	YES (IT IS INTRUSIVE BUT IN A POSITIVE WAY)	YES (AUDIO TONE WHEN CONTROLLING Nr IN AUTO NEAR THE GREEN BAND)	NO	NO	NO	NO	NO	NO	NO	3	10	0

Question 8 PLEASE RATE THE STRATEGY FOR AIDING ROTOR SPEED CONTROL IN AUTOROTATIVE FLIGHT

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	MEAN	STD DEV	MEDIAN
Baseline	2	2	4	4	4	2	6	5	5	3	1	5	6	3·77	1·64	4
Baseline+Prediction	4	2	3	5	3	4	6	4	6	3	4	5	6	4·23	1·30	4
Multitones	4	5	5	4	4	4	6	6	7	3	4	7	6	5·00	1·29	5
Tones+Messages	3	4	3	5	4	4	6	5	5	3	5	3	6	4·31	1·11	4
Enhanced Visual	6	4	4	6	4	4	7	6	6	3	6	7	6	5·31	1·32	6
Modulated Tone	6	4	6	5	5	6	6	7	6	6	6	7	7	5·92	0·86	6
Auto 1	5	6	4	6	?	4	7	4	5	3	5	7	6	4·77	1·88	6
Auto 2	2	4	6	4	6	6	7	4	5	5	5	6	6	5·08	1·32	5

Question 9 AT ANY TIME DURING THE SORTIE WERE YOU AWARE OF ANY DISCREPANCIES BETWEEN THE DISPLAYS AND THE ROTOR SPEED WARNING STRATEGY?

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	YES	NO
Baseline	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Baseline+Prediction	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Multitones	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Tones+Messages	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	YES (SEE ABOVE)	NO	1	12
Enhanced Visual	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Modulated Tone	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Auto 1	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Auto 2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13

Question 10 AT ANY TIME DURING THE SORTIE WAS THERE ANY CONFUSION ASSOCIATED WITH THE LOW ROTOR SPEED WARNING?

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	YES	NO
Baseline	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Baseline+Prediction	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Multitones	NO	NO	NO	YES (HYD AUDIO CONFUSED)	NO	NO	NO	NO	NO	NO	NO	NO	NO	1	12
Tones+Messages	NO	NO	YES (ALTHOUGH CONFUSION WAS TEMPORARY)	NO	NO (BUT MAYBE IT SHOULD SAY LOW Nr)	NO	NO	NO	NO	NO	NO	YES (REACTED INCORRECTLY TO HYD FAILURE)	NO	2	11
Enhanced Visual	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Modulated Tone	NO	YES (DUE TO SIMILAR SOUNDS BUT DIFFERENT TONES)	NO	NO	NO (BUT I'D HATE YOU TO THINK YOU'D GOT IT RIGHT!)	NO	NO	NO	NO	NO	NO	NO	NO	1	12
Auto 1	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	0	13
Auto 2	NO	NO	NO	YES (COLLECTIVE LOWERING FELT UNNATURAL)	NO	NO	NO	NO	NO	NO	NO	NO	NO	1	12

Question 11 IF THE LOW ROTOR SPEED WARNING STRATEGY CONTAINED A VOICE COMPONENT PLEASE RATE YOUR LEVEL OF SATISFACTION WITH THE VOICE COMPONENT

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	MEAN	STD DEV	MEDIAN
Baseline	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
Baseline+Prediction	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
Multitones	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
Tones+Messages	4	3	3	6	5	6	7	6	4	2	6	3	6	4·69	1·60	5
Enhanced Visual	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
Modulated Tone	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
Auto 1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
Auto 2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			

IF YOU RATED LESS THAN 7 ON QUESTION 11 PLEASE GIVE YOUR IDEAL SPECIFICATION FOR THE VOICE COMPONENT OF A LOW ROTOR WARNING STRATEGY

Tones+Messages	FIRST 'ROTOR' WARNING USEFUL. SUBSEQUENT DISTRACTING	LOW ROTOR RPM+TONE. HI ROTOR RPM+TONE		VOICE DID NOT STATE LOW OR HIGH	LOW OR HIGH SHOULD BE CONSIDERED	SEE QUESTION 11			VOICE OCCURS AFTER OTHER CUES AND ACTION HAS BEEN TAKEN.	VOICE IS POOR. HIGHER PITCH MAY INSTIL URGENCY.	PERHAPS TOO HARSH A VOICE. DIFFERENTIATE BETWEEN HIGH AND LOW Nr.	VOICE COMPONENT UNNECESSARY	A CONTINUOUS AUDIO SIGNAL WITH NO BREAKS

Question 12 PLEASE GIVE AN OVERALL RATING FOR THE ROTOR SPEED WARNING SEEN IN THIS SORTIE UNDER BOTH ATTENTIVE AND PASSIVE FLIGHT CONDITIONS

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	MEAN	STD DEV	MEDIAN
Baseline	2	2	4	3	3	2	6	5	5	4	1	6	5	3·69	1·65	4
Baseline+Prediction	5	3	3	4	3	5	6	4	6	5	4	5	6	4·54	1·13	5
Multitones	4	4	4	3	4	5	6	5	7	4	4	7	6	4·85	1·28	4
Tones+Messages	5	3	4	5	4	6	7	5	6	3	5	3	6	4·77	1·30	5
Enhanced Visual	6	4	4	6	4	4	7	6	6	4	5	7	5	5·23	1·17	5
Modulated Tone	4	4	5	5	4	7	6	7	6	5	6	5	7	5·46	1·13	5
Auto 1	6	6	5	7	?	6	6	5	5	3	5	6	6	5·08	1·80	6
Auto 2	3	7	6	4	6	6	7	5	5	6	5	6	7	5·62	1·19	6

Question 13 DO YOU FEEL THE STRATEGY SEEN IN THIS SORTIE COULD BE IMPROVED IN ANY WAY? IF YES PLEASE DESCRIBE YOUR RECOMMENDATIONS BELOW

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	TOTALS YES	NO	N/A
Baseline	YES	YES	YES	YES	YES	YES	YES	N/A	YES	YES	YES	N/A	YES	11	0	2
Baseline+Prediction	YES	YES	YES	YES	YES	YES	NO	N/A	YES	YES	YES	YES	YES	11	1	1
Multitones	YES	YES	YES	YES	YES	YES	YES	N/A	YES	YES	YES	NO	YES	11	1	1
Tones+Messages	YES	YES	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	YES	11	2	0
Enhanced Visual	NO	NO	YES	NO	YES	YES	YES	N/A	YES	YES	YES	YES	YES	9	3	1
Modulated Tone	YES	YES	YES	YES	YES	YES	NO	N/A	YES	N/A	YES	YES	YES	10	1	2
Auto 1	YES	YES	NO	N/A	YES	YES	YES	NO	YES	YES	YES	N/A	NO	8	3	2
Auto 2	YES	YES	YES	YES	YES	YES	NO	NO	YES	YES	NO	YES	NO	9	4	0

Baseline	TONES FOR FIRE HIGH Nr WARNING	ALREADY DISCUSSED	MODULATED TONE	AUDIO BLEEP FOR FIRE AND HYD. RPM HORN TOO SLOW	UNREALISTIC NOT TO HAVE M/C ATTENTION GETTER	TQ GAUGE BY PRIMARY INSTRUMENTS GIVES EARLY WARNING	WARNING WAS ACTIVATED WHEN Nr WAS VERY NEAR TO A LIMIT		HIGH Nr AUDIO AND MODULATION	1 – Nr RATE TERM. 2 – TONE WARNING NEEDS VISUAL CONFIRMATION	ALMOST ANYTHING WOULD IMPROVE IT!		PUSH DOWN
Baseline+Prediction	VARIABLE TONE/ FREQUENCY Nr WARNINGS	RATE AUDIO	MORE URGENCY REQUIRED – POSSIBLY VOICE WARNING?	HIGH AND LOW Nr TONE WOULD BE HELPFUL	MASTER CAUTION ATTENTION GETTER	VOLUME MODULATION INDICATION OF STEADY Nr MIN			MODULATION	RATE/ DISPLACEMENT FROM NORMAL Nr	INCLUDE EXTRA AIDS FROM OTHER STRATEGIES	INCLUDE OVERSPEED WARNING	AUTO PITCH UP
Multitones	INITIAL POWER LOSS INDICATION PRIOR TO THE Nr DROPPING	USE THIS + RATE LOGARITHM	ADD Nr RATE INFORMATION EG MODULATION OF THE TONE	VARIABLE TONE AND VOICE FOR WARNINGS	USE ATTENSONS FOR LESS URGENT FAILURES	MODULATE TONE	EARLIER WARNING		THE Nr/NF STRIP SHOULD BE MORE IDENTIFIABLE		BIGGER DIFFERENCE BETWEEN TONE WARNINGS		AUTO PITCH UP
Tones+Messages	INHIBIT SUBSEQUENT VOICE WARNINGS	AS QUESTION 11 COMMENT	SUPERIMPOSE VOICE MESSAGES ON A REDUCED VOLUME TONE			YES (SEE QUESTION 11)			MODULATION HELPS GREATLY – VOICE NOT SO	REDUCE SIMILARITY OF TONES	LACK OF TONE AFTER MESSAGE IMPLIES Nr IS OK	REMOVE VOICE MESSAGES FROM THE AUDIO	A CONTINUOUS AUDIO SIGNAL WITH NO BREAKS
Enhanced Visual		ARROWS HELPED DURING THE TURN	NEED TO INCREASE RESPONSE TIMES IN PASSIVE FLIGHT		DO AWAY WITH ARROWS!!	MODULATED TONE. REDUCE VISUAL CUE INCOMPATIBLE CUES	POSSIBLE USE OF VOCAL WARNING		MODULATION	LIGHT IS MORE OF A DISTRACTION	MODULATED TONE. USEFUL TO LOW TIME PILOTS	MORE PREDICTION WOULD BE NICE	DELETE HI Nr LIGHT
Modulated Tone	MORE URGENT INITIAL CUE	DIFFERENT TONES FOR OTHER EMERGENCIES	ENHANCE Nr RATE INFO?	EARLIER AUDIO WARNING WITH RPM DECAY	FLIGHT DIRECTOR	VOICE INPUT AT Nr LIMITS+ (AUTO1)			THE Nr/NF STRIP SHOULD BE EASIER TO READ		TONE BECOMES CONTINUOUS WHEN Nr IS URGENT	DIFFERENT ATTENTION GETTER	AUTO PUSH DOWN
Auto 1	VARIABLE FREQUENCY TONES FOR HIGH AND LOW	WHAT WOULD HAPPEN IF YOU WERE ABOVE 60KTS IAS?	NO			TONE MODULATION AND ANTICIPATION	CONCERN THAT A/C MAY ATTAIN AN UNUSUAL ATTITUDE		AS BEFORE – MODULATION	FLIGHT DIRECTOR	PITCH UP OK IN PASSIVE MODE Nr TONE COULD GIVE MORE INFO	PITCH UP DOES NOT AID PROBLEM IDENTIFICATION	
Auto 2	GENERALLY IN PASSIVE MODE IT SEEMS TOO EASY TO OVER REACT	IN AUTO AUTOMATIC INPUT TO CONTROL HIGH ROTOR RPM	VISUAL INDICATION THAT LEVER HAS BOTTOMED OUT	SLOWER COLLECTIVE CHANGE VAIRABLE AUDIO	AUTO 1 IS THE MOST PRACTICAL ANSWER	MODULATED TONE			MODULATED TONE PREFERRED		AUTO SYSTEM GAVE NO FEEL FOR THE RANGE OF COLLECTIVE AVAILABLE	?	

FINAL QUESTIONNAIRE

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13	MEAN	STD DEV	MEDIAN
Question 1	4	5	4	3	3	3	4	4	5	3	3	2	5	3·69	0·95	4·00
Question 2	4	5	4	3	3	4	5	3	5	4	4	5	4	4·08	0·76	4·00
Question 3	NO	YES (POOR HANDLING CHARACTERISTICS AND MECHANICAL CHARACTERISTICS WERE AT TIMES DISTRACTING)	NO	NO (IT WOULD BE BETTER IF A DAYS FLYING OCCURRED FIRST)	YES (THE CONTROL RESPONSE WAS NOTHING LIKE AN S61 OR AS332L THEREFORE I HAD TO FLY IT ON THE BEEP WHICH WAS NOT NATURAL)	NO	NO	YES (LACK OF FAMILIARITY)	NO (BEARING IN MIND THE LIMITATIONS OF THE SIM IE THE SIMPLE VISUALS)	YES (NO MOTION) CUES AND NO AURAL Nr DECAY THAT WOULD COME FROM HELICOPTER DYNAMICS)	YES (SLIGHTLY, BEEPER AWKWARD AND DISTRACTING	YES (POOR REALISM IN PARTICULAR LACK OF AMBIENT NOISE CUES)	NO			

Rank Order

														MEAN	STD DEV	MEDIAN
Baseline	2	1	2	5	1	1	2	1	1	3	1	2	2	1·85	1·14	2
Baseline+Prediction	5	2	4	6	5	3	3	2	5	6	3	4	5	4·08	1·38	4
Multitones	4	4	6	2	3	2	6	3	3	4	2	5	3	3·62	1·39	3
Tones+Messages	1	3	1	3	6	5	5	6	4	2	4	1	6	3·62	1·94	4
Enhanced Visual	7	5	3	4	2	4	4	4	2	5	5	8	1	4·15	1·95	4
Modulated Tone	6	7	7	7	4	8	7	5	8	8	8	6	7	6·77	1·24	7
Auto 1	8	6	8	8	8	7	1	7	7	1	7	3	4	5·77	2·62	7
Auto 2	3	8	5	1	7	6	8	8	6	7	6	7	8	6·15	2·12	7

IDEAL SYSTEM

	Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10	Pilot 11	Pilot 12	Pilot 13
AUDIO	FOR INITIAL RECOGNITION A POWER LOSS WARNING AS SOON AS Nr STARTS TO DECAY, FOLLOWED BY MODULATED TONES IN AUTOROTATION	LOW AND HIGH WARNING MUST BE ABSOLUTELY DISTINCTIVE. MODULATED TONE COULD BE GOOD DEPENDING UPON THE ROTOR'S RESPONSE	MODULATED TONES CAREFULLY OPTIMISED TO GIVE THE MAXIMUM AMOUNT OF Nr INFORMATION (VALUE & RATE). VOICE MESSAGE DOES NOT SEEM TO ENHANCE THE AURAL WARNING	MODULATED TONE – ENGINE OUT, VOICE FOR OTHER WARNINGS	IT MUST BE POSSIBLE TO PRODUCE SOME FORM OF DIRECTOR (ie COMMAND) IN EITHER AUDIO OR VISUAL OTHERWISE I WOULD SAY YOUR LOW NR TONE IS GOOD. THE OTHERS WERE NOT VERY GOOD	MODULATED TONE INTERMITTENT SIGNAL WITH FREQ REPRESENTING Nr SOUND i.e. LOW = LOW NR VOICE TO ANNOUNCE EXTREME LIMITS	MODULATED TONE WITH EITHER A VERY NARROW GREEN BAND OR AN ADDITIONAL TONE SIGNIFYING THE EXTENT OF THE GREEN BAND	INTERMITTENT FOR ENGINE FAIL/LOW Nr CONTINUOUS FOR OTHER WARNINGS	THE MODULATED TONE IS THE BEST LOW ROTOR WARNING I HAVE SEEN	MODULATED TONE BUT CONTINUOUS OUTSIDE REASONABLE Nr OPERATING BAND. ABILITY TO MUTE WARNING WITH A COLLECTIVE 'HOLD-ON' SWITCH	MODULATED TONE WITH SPOKEN MESSAGE FOR Nr LOSS: SPOKEN WORD SOFTER FOR OTHER MESSAGES USING CHIME AS AN ATTENTION GETTER	MODULATED TONE IS GOOD BUT NEEDS TO BE PART OF AN INTEGRATED WARNING SYSTEM AND WOULD ASSUME A VERY RESTRICTED NUMBER OF OTHER AUDIO TONES FOR UNCONNECTED EMERGENCIES	MULTI-TONE + MESSAGE BUT WITH CONTINUOUS TONE/ROTOR AUDIO FOR NR
VISUAL	LARGE VISUAL CUE ON INITIAL ROTOR DECAY. THE ENHANCED VISUAL CUES WOULD AID A 'VISUAL' AUTOROTATION BUT MIGHT BE DISTRACTING IN AN IFR AUTOROTATION	UP DOWN ARROWS USEFUL IF GAUGE DIFFICULT TO INTERPRET	IN BRIGHT SUNLIGHT CONDITIONS, VISUAL INDICATIONS ARE OF DOUBTFUL VALUE. HOWEVER AN INDICATION OF COLLECTIVE POSITION WOULD BE ESSENTIAL FOR THE AUTO PULL DOWN SYSTEM	ENHANCED VISUAL SYSTEM (NOT ESSENTIAL – MORE TESTING REQUIRED TO CONFIRM)	DID NOT LIKE THE ARROWS – SOME FORM OF SIMPLE COMMAND BAR TO FOLLOW MAY BE A GOOD IDEA. OTHERWISE YOUR STRIP GAUGE WAS QUITE GOOD	ATTENTION GETTER FOR CWP	POSSIBLY OVER DISTRACTING IN IMC AND OF LITTLE VALUE IN VMC	CENTRAL LIGHT	IMPROVE THE POSITION AND CONSPICUITY OF THE Nr/Nf STRIP	PITCH GAUGE TO CHECK WHAT GIVES ME A STEADY AUTOROTATIVE Nr AND ALLOWS ME TO SELECT MORE OR LESS PITCH, AHEAD OF AIRCRAFT DYNAMICS DRIVING IT e.g. EXTRA 1/2 DEGREE OF PITCH PULLED BEFORE ENTERING A TURN WOULD STOP THE ACCELERATION OF THE ROTOR	ENHANCED VISUAL DISPLAY WAS OK. PERHAPS OF GOOD VALUE TO A LOW TIME PILOT AND WHEN SEARCHING FOR LANDING SITE	I LIKED THE HIGH AND LOW LIGHTS AS PRESENTED.	NOT NECESSARY
TACTILE	NOT SURE!	AUTOMATIC COLLECTIVE REDUCTION EXCELLENT	THE SIMULATION OF AUTO-FLARE IN THIS TRIAL RESULTED IN MINIMAL LOSS OF NR AND INCREASED AVAILABLE RESPONSE TIME SIGNIFICANTLY. SUCH A SYSTEM MIGHT OVERCOME THE REDUNDANCY PROBLEMS POSED BY THE FULL PULL DOWN SYSTEM	GRADUAL FLARE	STICK SHAKER DOES NOT SOUND VERY GOOD			VIBRATION AUTOMATIC LOWER OF COLLECTIVE	AUTOMATIC INTERVENTION (1) + 2	I LIKE THE PULL DOWN COLLECTIVE IT WOULD MAKE AN EXCELLENT COMBINATION WITH A COLLECTIVE DRIVER WHICH AUTOMATICALLY GAVE MAX POWER AT OE!	PERSONALLY FOUND THIS MORE DIFFICULT TO ASSESS. POSSIBLY FOUND THIS HELPFUL DUE TO SIMULATOR UNFAMILIARITY ETC?	THE COLLECTIVE DRIVER IS GOOD	
OTHERS	EFFORT SHOULD BE DIRECTED ON EARLY DETECTION OF POWER LOSS AS OPPOSED TO NR DECAYING THROUGH A MINIMUM FIGURE	AUTOMATIC COLLECTIVE INCREASE TO LIMIT HIGH RRPM IN AUTOROTATION				AUTO 1 FOR CRUISE CONDITION (SAY 90KTS PLUS)	IDEAL SYSTEM AUTOMATED INTERVENTION 1 WITH MODULATED TONE AS DISCUSSED UNDER AUDIO ABOVE						