Civil Aviation Authority

CAA Paper 85012

Report of the Working Group on Helicopter Health Monitoring

Price £2.50

Civil Aviation Authority London August 1985

CAA Paper 85012

Report of the Working Group on Helicopter Health Monitoring

This Paper presents the Report of the Health Monitoring Working Group convened by the CAA in response to one of the Recommendations of the Helicopter Airworthiness Review Panel (HARP); the HARP report was published as CAP 491. The Group comprised experts from industry and MOD as well as CAA specialists. This Report therefore reflects the views of that Group rather than defining CAA policy.

The CAA is grateful for the work of the Group and believes generally that their Conclusions and Recommendations should be strongly supported. The CAA would like the Group's Report to be widely considered relative to the future role of Health Monitoring.

Civil Aviation Authority London August 1985

ISBN 0 86039 250 3

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

CONTENTS

HELICOPTER HEALTH MONITORING

SUMMARY

The Health Monitoring Working Group was convened by the CAA and first met on 27 March 1984, membership was drawn from Industry, the Ministry of Defence and the CAA. Terms of Reference to satisfy the Helicopter Airworthiness Review Panel's recommendation No 11 were established. Specifically, this suggested that experts in the Airworthiness Division, Ministry of Defence and selected specialists should draw up proposals for parameters to be measured, and for new or improved condition monitoring devices or systems.

The Working Group reviewed the current 'state of the art' and considered the proposed Airworthiness Requirements for future helicopters, seeking to define the health monitoring improvements which would be needed to realise the intended safety objectives.

The Group recognised that major benefits could be expected from exploiting Health Monitoring, not only on future helicopters, but also by retrospective application to those currently in service, and this aspect has been included in the report.

The main conclusions drawn from the study were:-

(i) - Health Monitoring is particularly relevant to the transmission, rotor systems, flight control system and engines

(ii) - current technology can provide airworthiness and reliability benefits

(iii) - Research or application development is required in respect of:

- vibration analysis, wear debris monitoring, pressure temperature and flow sensors
- optical fibre strain detectors
- electrical resistance strain gauging and FM telemetry
- optical sensors, data banks and interfaces for fly-by-light helicopters
- more accurate/intelligent blade tracking facilities
- FM telemetry torquemeters
- on-board detection of oil contamination
- application of Expert Systems technology
- on-board processor/interface/display development
- ground based data management systems
- 'smart' sensors

(iv) Details of the timescale for the research and development activity.

Specific recommendations were made in relation to the Terms of Reference, but in addition the Group recommended:-

- efforts to encourage international agreement on the requirement for health monitoring
- the formation of a Helicopter Health Monitoring Advisory Group
- the increased application of health monitoring to existing helicopters which are likely to remain in service for an extended period.
- the use of demonstrations and in service trials to promote health monitoring.

1 INTRODUCTION

The report of the Helicopter Airworthiness Review Panel (HARP) was published, as CAP 491, by the Civil Aviation Authority in June 1984. Recommendation 11 of that report states:

> "Recommendation 11 The CAA should set up a working party between experts in the Airworthiness Division, Ministry of Defence and selected specialists from universities and industry to draw up proposals or requirements for parameters to be measured and for new or improved condition monitoring devices or systems, to be widely publicised."

The CAA was aware of this recommendation from the earlier draft HARP report and in January 1984, the Director-General, Airworthiness Division set up such a Working Group. The Group held its first meeting in March 1984 and its work programme was covered by eight meetings of the main Group plus numerous informal and sub-group meetings.

The terms of reference for the Group, as finally agreed, are given below.

"Having regard to the airworthiness objectives now being considered appropriate for future helicopters, the Working Group will:-

1 Identify the areas in which Health Monitoring is likely to be a necessary or preferred means of achieving those airworthiness objectives.

2 Establish the extent to which existing technology is capable of providing the required Health Monitoring.

3 Identify the areas where existing technology does not meet the need and suggest the timescale in which the shortfall should be made good.

4 Recommend the means by which additional technology should be researched and developed.

5 Advise on the principles that should apply to Airworthiness Requirements for Health Monitoring.

6 Report to the Director-General, Airworthiness, CAA within one year.

Notes: 1 The Working Group should consult other Airworthiness Authorities, industry, and other experts as felt to be appropriate.

2 Health Monitoring is concerned with extracting information from machines to indicate their condition, and to enable them to be operated and maintained with safety and economy.

3 Usage Monitoring will be taken into account where it is considered relevant to achieving the airworthiness objectives.

It should be noted that in choosing the title "health monitoring" rather than "condition monitoring" as stated in the HARP recommendation, the Group recognised that the term "condition monitored" had another specific meaning in the aircraft maintenance fraternity.

The membership of the Group was chosen to represent as wide a range of interests as possible, while retaining the size of the Group at a level consistent with efficient working. Industry representation included the main UK helicopter and engine manufacturers, operators at both aircrew and engineering level, and equipment manufacturers. This latter group of interested parties is very large within the UK and it was decided to seek the assistance of ESASC (Electronic Engineering Association and Society of British Aerospace Companies Avionics Systems Committee) who nominated a single representative who liaised with, and co-ordinated the comments of, his colleagues in the other interested Companies. Liaison with military activities in similar fields was achieved through the MOD(PE) member of the Group. The strong CAA interest in this activity is shown by the involvement of eight senior members of staff, drawn from the various airworthiness departments involved, plus the Chief Scientist's department, and provision of the Chairman and Secretary for the Group.

The membership of the Group is given in Appendix 1.

2 GENERAL

In determining the exact terms of reference of the Group and in subsequent discussions, it was very apparent that it is difficult to isolate "health monitoring" as defined in the terms of reference, from the other related activities particularly "usage monitoring" and "status monitoring". While accepting that its main-stream activity was to look at the health monitoring aspects in relation to the airworthiness objectives for future helicopters, the Group accepted that it also needed to be aware and take account of these related areas in so far as they are relevant.

In particular, it was appreciated that the actual implementation of health monitoring techniques in the rotorcraft will, most probably, be integrated with other related monitoring activities. This is to be encouraged since this may well help to provide an additional commercial impetus to the use of health monitoring techniques in addition to that provided by the new airworthiness requirements, and will make the total monitoring package more cost effective. The relationship between the Group's activities and the flight deck environment, particularly relative to crew work load, was recognised and liaison was established with the Human Factors Special Study Group and the work on the helicopter flight deck at Royal Aeronautical Establishment, Bedford.

To enable the Group to take account of work done by other parties, which was of interest to them, detailed presentations were made by Ministry of Defence MOD(PE) on their military programme and by Westland Helicopters on their activities in this and related areas. The time and effort spent by these organisations in making this information available to the group is much appreciated.

From enquiries made within the USA and Europe, the Group has not been able to find any other Airworthiness Authority who is encouraging, in particular, the use of health monitoring techniques, thus no useful liaison has been possible. However, it is strongly recommended that liaison with other Airworthiness Authorities be maintained, in particular to ensure that international airworthiness requirements on this subject are consistent.

Worldwide information on about 100 helicopter accidents caused by mechanical failure was obtained both from the CAA Safety Data Unit and from the appropriate sections within the Royal Navy, Royal Air Force and Army Air Corps. It was hoped that the information obtained concerning these accidents might point to the areas of the helicopter where health monitoring would be most beneficial. It was felt by the Group, that there was insufficient detail in the accident data to make any valid judgement. It would be necessary to examine each of the accidents in some considerable detail. This was not possible in the time available although, given appropriate specialist help, such a task would be feasible and is recommended by the Group. It must be stressed that in many cases, accurate information is sparse.

The Group kept itself abreast of related activities by representative attendance at relevant conferences, such as the Swansea University and RAeS conferences and by maintaining a list of related and relevant papers and reports. Most of these papers and reports were supplied by the industry sub-group and are listed in Appendix 2.

2 GENERAL (cont.)

Initially five sub-groups were set up to look at, in detail, various areas of the helicopter to determine the critical components and systems where health monitoring would contribute to airworthiness and to look at the techniques available for such monitoring now and in the future. These sub-groups covered transmission, flight mechanics and associated systems, propulsion, airframe and dynamic structure and avionic and other systems.

The results of these sub-group reports are discussed in section 3.2 of this report.

An additional sub-group took the reports from these sub-groups and used them as a basis for determining where existing technology is capable of providing the required health monitoring and advising on where research and development activity is required. The conclusions of this sub-group are considered in detail in section 3.3 of this report.

The CAA members of the Group have reviewed the relevant Airworthiness Requirements and, based upon this work, recommendations on the principles which should apply to future airworthiness requirements for health monitoring are also made. These are discussed in more detail in section 3.5 of this report.

While liaison with the on-going Ministry of Defence programmes on Health Monitoring and related activities took place during the Group's study period, the time scale for the issue of this report did not allow full consideration of the MOD reports being prepared on a wide range of vibration monitoring applications under Naval, General & Air Staff Target (NGAST) 6638. For future reference a list of the MOD reports under preparation is attached as Appendix 6.

3 DISCUSSION

3.1 Requirements proposed for future helicopters seek to achieve improvements in helicopter safety and are summarised in the following extract from BCAR Working Draft paper G.780.

- "The design of rotorcraft shall be such that with the exception of the Rotor and Transmission System the probability of a Catastrophic Effect from all system causes is Extremely Remote.
- The design of rotorcraft to be certificated in Group A shall be such that, with the exception of the Rotor and Transmission Systems, the probability of failure from all causes resulting in an emergency landing within a specified period of time, which shall be not less than 10 minutes, is not greater than Extremely Remote."

The rotor and transmission systems are subjected to the same considerations with the exception that the probability term 'Very Remote' is used in place of 'Extremely Remote'.

The terms used above are defined in BCAR Section G.

It was noted that compliance with these 'design objectives' would involve the use of Safety Assessment techniques.

The helicopter has been recognised as being fundamentally different to its fixed wing counterpart, evident by the fact that it is implicit in fixed wing requirements that all critical failures shall be sufficiently infrequent, by virtue of integrity or duplication, for operational constraints to be unnecessary.

The helicopter differs in two fundamental ways:-

(i) The mechanical features, particularly in the rotor and transmission systems, eg, gears, bearings, seals, lubrication, are unlikely to reach an inherent level of freedom from failure equivalent to that of the structure of current fixed wing aircraft. There is, for example, less opportunity to duplicate vital transmissions and power plant paths to match the level of fixed wing safety.

(ii) A forced landing can be a less hazardous event than for fixed wing, and will be reasonably survivable provided that the rotorcraft is not over hostile surface. The latter effect permitted the declaration of the 10 minute rule mentioned above.

Current mechanical systems with the complexity found in a typical helicopter are unlikely to satisfy the reliability criteria for integrity associated with Group A operations if reliance continues to be placed only on certification testing, safe lives established at that time based on assumed opperational flight spectra and the traditional life development in service. The latter is of decreasing benefit as the time between overhauls is increased.

Damage tolerance as an acceptable approach for preventing structural failures can also be directly relevant to many dynamic components in the Rotor and Transmissions Systems. Some damage tolerance concepts are equally relevant to the internals of gearboxes, but depend on the availability of suitable monitoring techniques to detect the onset of damage.

3 DISCUSSION (cont.)

If higher levels of reliability are to be achieved, recognition has to be given to the fact that many failure mechanisms are not strictly age related, therefore effective health monitoring techniques must be applied throughout the life of the component.

3.2 The Terms of Reference given to the five sub-groups, described in Section 2, were to:-

(i) Identify Critical areas where effective health monitoring would contribute to airworthiness.

(ii) Determine the techniques which are needed for this monitoring and indicate (if known) whether available or not.

(iii) Determine whether awareness is necessary on the flight deck, or during maintenance activity (or both), and recommend suitable presentation.

(iv) Consider the health monitoring requirements for foreseeable future helicopter technology.

For this part of the task, the helicopter was considered in the following discrete sections:

Sub-group 1 - Transmission

Including main and tail rotor gearboxes, intermediate shafts, bearings, mechanical aspects of rotor heads and rotating controls.

Sub-group 2 - Flight Mechanics and Associated Systems

Including flying control actuators, control runs, hydraulic systems and rotor brakes.

Sub-group 3 - Propulsion

Including the engine, engine control system, power plant items, fuel systems.

Sub-group 4 - Airframe and Dynamic Structure

Including structural aspects of the airframe, undercarriage, rotor systems, blades lift load paths, controls.

Sub-group 5 - Avionic and Other Systems

All systems not covered by Sub-groups 1 - 4, including the health monitoring systems.

The results of this work are summarised in Appendix 3. It was apparent that considerable need exists for additional health monitoring and it was necessary to research the means by which this should be provided.

3 DISCUSSION (cont.)

3.3 Subsequently an Industry Sub-Group was formed, the membership of which is given in Appendix 1. This Sub-Group had as its nucleus the industry representatives and made use of additional expertise from industry and MOD establishments.

This group was tasked to:

A Consider the summarised conclusions of the five sub-groups, in relation to items 2 and 3 of the Health Monitoring Working Group Terms of Reference and report accordingly; ie:

"2 Establish the extent to which existing technology is capable of providing the required Health Monitoring.

3 Identify the areas where existing technology does not meet the need and suggest the timescales in which the shortfall should be made good."

NB The study should clearly indicate:

- what can be done today

- which Health Monitoring methods need development

- which Health Monitoring techniques require research

B Provide an estimate of the effectiveness, usability, availability and cost of the various techniques.

The Industry Sub-Group's Report is included in Appendix 4. It will be noted that the first Sub-Groups identified potential health monitoring techniques, whereas the Industry Sub-Group developed this, considering discrete sections of the rotorcraft.

3.3.1 GENERAL

During completion of their task the Industry Sub-Group found that the current state of development and experience gained to date is such that further retrospective application of health monitoring techniques could provide significant benefits to existing designs of helicopter as well as developing designs.

In summary, the Sub-Group found that:-

(i) Whilst several health monitoring techniques applied to transmissions and engines have exhibited inadequacies, techniques introduced more recently have demonstrated inherent superiority especially when applied in combination, for example the Quantitative Debris Monitoring System and Enhanced Vibration Signal Analysis techniques (see Appendix 4). Several gearbox rig tests to failure have demonstrated the diagnostic and prognostic capability of this combination, and service experience to date has demonstrated freedom from spurious indications.

(ii) Retro-fit application may not result in optimum systems in terms of performance or reliability, but will nevertheless contribute to improved airworthiness.

(iii) The preferred approach to improved airworthiness is by means of on-board data processing systems and associated sensors. These systems provide immediate after-flight information on airworthiness for the next flight without the need for ground support equipment, skilled appraisal of passive diagnostic devices, or removal of oil or data samples for analysis in a laboratory. They also should be capable of alerting the pilot to situations to which he must react. A number of such systems are now in various stages of maturity, varying from engine performance monitors to very comprehensive systems addressing the health and usage monitoring of all mechanical systems within the helicopter.

(iv) Many of the techniques (current and developing) reviewed are specific to major components and failure modes. Techniques of more general application include:

- vibration analysis
- application of Expert Systems technology
- optical sensors particularly for helicopters of the future using optical data transmission.

(v) In addition to the need to monitor in-service aircraft, airworthiness benefits accrue from:

- application of the techniques to production quality assurance tests on components and aircraft
- application of Health Monitoring techniques during development and certification tests on components and aircraft
- feedback of Health Monitoring data from service, production and development sources to design.

3.3.2 Transmissions

This section includes main and tail rotor gearboxes, intermediate shafts, bearings and rotor brakes.

There is some scope for damage tolerance in gearbox design, provided by the gear configuration, which can influence the number of components in the critical load path of a twin engined helicopter and the secondary damage that can develop from an isolated primary defect. However, although it will be some time before damage tolerance could be the primary method of airworthiness control for transmissions and "safe life" continues to be the certification basis, there is an increasing role for health monitoring to provide additional assurance against premature failure.

Experience shows that a single health monitoring technique cannot satisfy all requirements. The wide variation in gearbox configurations, casing structures and design practices generally, means that a health monitoring method that works well in one gearbox may not succeed or be necessary in another.

3.3.2.1 Transmission System Health Monitoring Requirements

Health monitoring of gearbox internals should provide:

(i) Advanced warning of failure modes or potential defects.

(ii) Clear rejection signal for developing failure modes such as wear or fracture.

(iii) NDI techniques to aid and confirm diagnosis and detect corrosion.

In addition to wear debris monitoring, oil system monitoring should be concerned with oil system operation in all its aspects and to an extent, oil condition, including contamination.

The principal requirements for wear debris monitoring systems are high debris transport, capture and indicating efficiencies taking account of any ultrafine filtration in the system.

3.3.2.2 Transmission System Health Monitoring - Current Systems

A wide range of systems in various stages of maturity are reviewed in Appendix 4 under three headings - (i) on-line, (ii) aircraft ground inspections, (iii) laboratory based techniques. Some of the more effective on-line techniques are referenced here:-

- quantitative debris monitor
- pulsed electric chip detector
- vibration analysis, including enhanced time averaging
- shock pulse monitoring for shaft hanger bearings
- strain-gauge FM telemetry torquemeters
- remote oil level measurement.

3.3.2.3 Transmission System Health Monitoring Development - Short Term

Outstanding problem areas requiring system or algorithm development:-

- Material defects - gears and shafts
- Corrosion - internal components and casings
- Casing fracture
- Mal-distribution of load in planetary gears
- Contamination - metallic, non-metallic, water
- Influence of environment on health monitoring signals
- Sensor development - reliability and cost
- Rotor brake overheating.

3.3.2.4 Transmission System Health Monitoring Development - Long Term

There is scope for future technology to provide:-

- Total on-board monitoring/maintenance systems - computer based flight and maintenance manuals
- Application of Expert Systems to above, including the generation of maintenance data bases
- 'Smart' sensors with dedicated processing and control interfaces.

3.3.3 Rotor System

This section includes rotor blades, hubs, dampers, rotating anti-vibration features, and rotating control systems.

The airworthiness of current rotor systems is controlled by safe life procedures, aided by limited health monitoring, NDI facilities, ground inspections (visual/manual/torque checks), and pilot reported exceedances of torque and R.P.M limits, impacts, etc. New rotor head and blade designs make increasing use of fibre composite materials which exhibit markedly slower fracture propagation rates than metal components, and different modes of degradation (delamination, disbonds, water up-take etc) enabling a damage tolerance approach to be taken in design. Replacement of rolling element bearings by elastomeric bearings leads to a reduced number of moving elements, but variability in degradation remains a problem.

There is however, considerable scope for enhanced health monitoring systems, NDI techniques, and comprehensive usage monitoring in view of the potentially damaging effects of unanticipated loads.

3.3.3.1 Rotor System Health Monitoring Requirements

The requirements are similar to those listed in 3.3.2.1 for transmission system.

Effective, reliable means of signal transmission from rotating components are required, whether electrical, optical or by other means.

Fracture propagation rates can be very high, therefore an on-board detection capability with an ALERT warning to the pilot would be advantageous. It is unlikely that remote analysis of recorded data can provide sufficiently rapid response, there is however scope for ground-based or portable carry-on equipment for diagnosis of faults.

3.3.3.2 Rotor System Health Monitoring - Current Systems

A number of systems are available in various stages of maturity. Some of the more effective on-line techniques are referenced here:-

- Blade spar fracture - pressure/vacuum leak systems
- Control rods (hollow sections) - pressure/vacuum leak systems
- Blade tracking sensors
- Signal transfer systems (rotating component to structure)
- Ice accretion detectors - important to differentiate between ice and faults

3.3.3.3 Rotor System Health Monitoring Development - Short Term

In process of development are:-

- Short range FM telemetry signal transmission systems
- Long-life strain-gauges and straingauge torquemeters with wide frequency band widths
- On-board vibration data processing facilities
- Advanced rotor track and balance facilities
- Optical fibres and microwave coatings, for crack detection
- Expert systems technology applied to rotor diagnostics
- Lubrication system debris monitoring

3.3.3.4 Rotor Systems Health Monitoring Developments - Longer Term

Continued development of:-

- Ground-based equipment, aided by Expert Systems, to speed resolution of the many possible faults that can effect vibration at shaft orders and blade passing orders.

- Blade tracking equipment and associated processing/ display facilities to permit rotor tuning in all weather conditions with minimum of special flights.

- Certificatable on-board Expert Systems to aid discrimination between defects, trim requirements, ice accretion, and minor damage.

- NDI aids for in service helicopters, noting the increasing use of fibre-composite materials, elastomeric bearings.

- Integral fibre strain detection system with respect to defect propagation in fibre composite components

- Signal transfer means from rotating components to the structure.

3.3.4 Flight Control Systems

This section includes pilot's controls, non-rotating control systems, electrical and hydraulic power supplies, stability augmentation systems, Active Control Systems, and Higher Harmonic Control Systems.

On fixed wing aircraft airworthiness in flight control systems is generally provided by redundancy or duplication of complete systems. However, on rotorcraft single load path, safe-life systems are still the order of the day although currently CAA have draft proposals in hand with the object of providing redundancy on Group A rotorcraft of the next generation. (Paper G749). Critical single path features tend to be control jack bodies, attachments and attachment structure, and control linkages, and these are covered by safe-life procedures.

Experience indicates that duplication of systems does not always provide adequate protection against failures and hence there is scope for health monitoring. However each alternative function should be exercised regularly to reduce the likelihood of failures remaining undetected, by facilitating health monitoring.

Critical units within hydraulic systems such as servo-valves are by their action prone to hard-over/control runaway failures due to mechanical disconnects or false electrical signals, also to sticking due to particle contamination of the fluid. This, plus the mechanical aspects of hydraulic and electrical power systems (including gearbox auxiliary drives) are amenable to existing health monitoring techniques.

Control systems are required to have stiffness characteristics compatible with control stability. Wear or cracking of components in the linkage can therefore potentially be manifest in modification of control responses resulting in changes in vibration characteristics and loads within the system, or difficulties in control of the rotorcraft.

Active and Higher Harmonic Control Systems should have in-build diagnostic capability. Such Systems will have the ability to alleviate loads imposed on the structure and dynamic components, and must have the ability to detect system faults which could otherwise be disguised.

3.3.4.1 <u>Flight Control Systems - Current Health Monitoring Techniques</u>

- Hydraulic Systems - fluid pressure, temperature
  - contamination
  - servo-malfunction indication

- Electrical Systems - voltage, current, frequency

- Linkages and bolts - pressure/leak
  - indicating valve
  - bleeding bolts

- Control thrust bearings - temperature

3.3.4.2 <u>Flight Control Systems - Health Monitoring Developments - Short Term</u>

In process of development are:-

- Hydraulic Systems - contamination - reversing indicating filter - Optical sensors

- Powered control units and linkages - loads/strain

- Input/output comparison

3.3.4.3 <u>Flight Control Systems - Health Monitoring Developments - Longer Term</u>

There is scope for:-

- Optical sensors Ref. to para 3.3.1 (iv) helicopters.

- Vibration analysis for control linkage wear/fracture and wear in hydraulic pumps.

- Application of Expert Systems technology for fault diagnosis

- Health Monitoring developments within Active Control Systems.

3.3.5 Structures

This section includes the whole of the aircraft structure including gearbox casings and attachments and active or passive undercarriages.

The potential contribution of advanced health monitoring systems to the airworthiness control of structures and undercarriages is limited as direct damage tolerant design can be introduced for many areas.

For existing helicopters, safe life procedures are employed, although increasing use is being made of the damage tolerance approach in terms of alternate load paths in some critical areas.

For future helicopters, rules are being formulated to require the damage tolerance approach unless impractical. Health monitoring has a role to play in extending the damage detection capability of current inspection techniques and increasing the practicality of damage tolerance design e.g. in undercarriages. Both damage tolerance and safe life approaches can be enhanced by employing usage monitoring to establish the operational loads in key locations to correlate with design assumptions.

3.3.5.1 Structures - Current Health Monitoring Techniques

- Vibration analysis - Rotor order check list procedure, Narrow band frequency spectra.

- Mechanical Strain recorders.

3.3.5.2 Structure Monitoring Developments - Short Term

In process of development:-

- Load Data and Operational Data recording survey systems

- Optical fibre and microwave coating crack detectors.

3.3.5.3 Structure Health Monitoring Developments - Longer Term

Research and development:-

- A means of assessing environmental influences on composite materials

- Health Monitoring aspects of active isolation systems for dynamic components, to prevent the masking of failures.

- Health Monitoring of elastomeric bearings, anti vibration mounts and other means of vibration attenuation at gearbox/structure interface.

3.3.6 Engines and Fuel Systems

The flight critical aspects of civil helicopter power plants are rotor and casing integrity, structural attachments, failure of the common fuel supply system, and fire suppression. Major factors relating to engine integrity are rotor disc burst and blade loss.

Main bearing integrity is also a factor but damage progression rates are lower. Integrity of oil sealing and oil pipes is also important relative to fire hazards. Engine performance degradation and the correct functioning of power/speed limiting devices are also important airworthiness issues, particularly in operations from oil rigs and heli-pads.

3.3.6.1 Engine & Fuel system Health Monitoring Requirements

The principle methods of controlling the integrity of fuel systems, engine attachments, and fire suppression equipment is by redundancy and routine checks. Health, Usage and Performance Monitoring activities relating to the Engine Change Unit have six main objectives:

(i) To provide close control of usage of components designed on a safe-life basis.

(ii) To maintain up to date evidence that each engine is capable of producing its single engine power rating reliably, ie, Power Assurance.

(iii) To quantify the use of the engine within the certified rating structure, including limit exceedance.

(iv) To permit safe extension of the rating structure for emergencies.

(v) To provide data to assist the analysis of wear modes and damage progression within oil wetted parts of the engine, including bearings.

(vi) To provide shaft imbalance monitoring (eg, tracking filters).

3.3.6.2 Engine - Current Health Monitoring

Currently approved monitoring techniques are similar to those listed under Transmissions. These are supplemented by pilot observations which, post flight, are converted into power assurance values and low cycle fatigue (LCF) cycles using a bulletin chart.

3.3.6.3 Engine - Health Monitoring Developments

Outstanding areas are:-

- Refinement of algorithms associated with:

  (i) Low Cycle Fatigue (LCF) of all critical engine components

  (ii) Creep usage of HP/LP turbine blades

  (iii) High Cycle Fatigue of drive shafts

  (iv) Power Performance Index (PPI)

  (v) Limit Exceedance Logic

- Corrosion, internal components and casings

- More detailed understanding of failure modes and response characteristics to assist interpretation of vibration signals

- Improved engine performance diagnostic routines

- Continued development of wear debris monitoring

- Monitoring of all aspects of oil system operation

- Logistics of data management off the aircraft

Wear debris and vibration monitoring are discussed in detail in the Transmission section. Most of the comments made also apply to engine component monitoring although differences in temperatures, oil scavenging, gear tooth loadings, and other factors can be expected to produce differences in vibration and wear debris characteristics and rejection criteria.

3.4 COST EFFECTIVENESS

The cost effectiveness of health monitoring systems requires careful consideration. In the attachment to Appendix 4, an estimate of overall feasibility is given which takes broad account of performances, reliability, cost, weight, workload, response time, compatibility and justification, resulting in an overall estimate of timescale for implementation.

The cost, weight and reliability implications differ between application to future helicopters, and retrospective application to helicopters currently in service.

(i) Future aircraft. The cost driver for a new design of system is the requirement for development rig testing or dedicated test flying to accumulate experience, confidence and verify and modify software and possibly hardware. However, sensor reliability and system integrity is likely to be better where equipment is selected and fitted as an integrated part of the initial design process. Also, the greatest gains can be made in TBO extension because the system contributes to, and accelerates the development and early service TBO growth programme.

Additional cost advantages are:

(a) Application of techniques in production QA tests for new build components

(b) Early feedback of condition performance data to assist in the design of early reliability modifications

(c) Inclusion of development data in certification tests

(ii) Retro-fit Systems. Many existing helicopter types will remain in service for the next 10-15 years. For a particular component, in introducing a health monitoring technique in retrospect, the component TBO against actual failure rate must be considered. If the component regularly achieves TBO, then the cost benefit of retro-fit action will come in the extension of TBO to, 'on condition', as well as the bonus of an additional tool for improved airworthiness useful for the whole life of the component. Against this must be set the cost of modification hardware, and the programme of rig/development testing to achieve certification.

For systems not currently achieving TBO in the specific operating environment, type of failure will determine the justification, or otherwise, for improved airworthiness by this means. Retro-fitting a health monitoring system will probably prove cost effective because in addition to reducing the chances of a catastrophic failure, the data obtained can be used in the design process to produce timely reliability modifications.

Retro-fit systems also provide improved operating and maintenance flexibility resulting from failure diagnostic and predictive information.

The existing airworthiness requirements do not prevent advantage being taken from the retro-fit of suitable health monitoring equipment, particularly in respect of maintenance activities.

3.5 AIRWORTHINESS REQUIREMENTS

The Working Group reviewed the requirements scene and concluded that there is a need for a general requirement to allow both credit to be given for the use of Health Monitoring and to encourage the use of such techniques where they are necessary to ensure that the desired level of safety can be achieved. It is recommended that suitable requirement material be added to BCAR Chapter G4-1 Design and Construction - General, and C4-2 Design and Construction (Turbine Engines for Rotorcraft), to which cross-reference can be made from other relevant requirement chapters, such as structures, where the use of Health Monitoring Techniques will be encouraged as an extension to existing inspection techniques.

The requirement proposed in BCAR Paper No. G.811 (2nd draft of issue 1) dated 31st December 1984 (See Appendix 5) provides suitable material for discussion with interested parties as a basis for inclusion in BCAR Sections G and C (G4-1 and C4-2) and other equivalent codes. Among the changes necessary would be the broadening of the rotor and transmission systems and cross-reference to Paper G.803 Safety Assessment of Aircraft Systems.

With the provision of such material in G4-1 and C4-2, then consideration should be given to including suitable cross-references in G4-9.

The requirements related to maintenance issues were reviewed, taking account of those which already exist or are being developed. This work did not reveal the need for further changes except in so far as the MMEL is concerned. The details are included in Appendix 5.

4 CONCLUSIONS

4.1 General Conclusions

(i) The Group concludes that significant advances are being made in Health and Usage Monitoring technology and some have already been applied to certain existing helicopters. These advances were introduced before publication of the HARP report. This reflects the on-going commitment of helicopter and engine manufacturers, operators, MOD, equipment manufacturers, universities and research establishments to advancing Health Monitoring technology in parallel with other reliability improving technology to achieve improved airworthiness.

These techniques include:-

Transmissions

On production:-

- quantitative wear debris monitoring
- pulsed electric chip detector
- advanced vibration analysis
- borescope and guide tube provisions (for in-situ confirmation of wear.)

Under development:-

- FM telemetry torquemeters
- torque exposure/cumulative damage data processing
- on-board vibration analysis
- portable vibration analysis equipment

Rotor Systems

On production:-

- blade spar integrity detection

Under development:-

- strain gauged hubs and FM telemetry
- improved blade tracking facilities

Engines

On production:-

- shaft vibration (tracking filters)
- cycle-counting (low cycle fatigue and creep)
- Power Assurance monitoring

4 CONCLUSIONS (Cont'd)

4.1 (Cont'd)

General

On production:-

- portable analysers for vibration

Under development:-

- comprehensive on-board monitoring systems
- high frequency vibration data acquisition and analysis on-board
- debris and oil analysis (several)
- Health Monitoring system comparative evaluations on development and service aircraft and component rig tests
- optical fibre strain sensors for blades, hubs and structures
- application of Expert Systems to algorithm development.

(ii) There is no panacea as far as health monitoring of helicopter components and systems is concerned. Particular techniques may be more suitable to a particular helicopter and its systems and components, and more than one technique is often required in order to contain possible failure modes.

(iii) In future designs of helicopters the areas that, from an airworthiness point of view, would benefit most from the use of Health Monitoring Techniques are transmissions and rotor systems. These are flight critical systems for which the Damage Tolerance approach has limited scope using current inspection techniques but would be greatly extended by effective Health Monitoring for damage detection. Engine usage and power assurance and rotor control systems are also important areas for effective monitoring systems. Rotor track and balance systems will also contribute to airworthiness.

(iv) For existing helicopters, which are likely to remain in service for an extended period, similar conclusions to those stated in (iii) above also apply. Such retrospective installations are subject to the constraints which are discussed in more detail within this report.

(v) Health Monitoring should be an integral part of the total maintenance strategy and system, whether this be on-board, and/or ground-based. Usage Monitoring, Performance Monitoring, and Status Monitoring also contribute to improvement of airworthiness and may well form part of the same integrated system.

(vi) The Health Monitoring system itself must be of high integrity and reliability if airworthiness credit is to be given for its output. The system must not adversely affect the airworthiness of the components monitored. Again, if credit is to be claimed for use of the system, it may need to be a "NO-GO" item on the Minimum Equipment List for the aircraft, or a time limit defined for its repair/replacement.

4 CONCLUSIONS (Cont'd)

4.1 (Cont'd)

(vii) Flight deck indications from the Health Monitoring systems need to be integrated with the warning philosophy for the particular aircraft and should normally be limited to parameters where there is a "need to know".

(viii) "A damage tolerant design with a vibration health monitoring Expert System to alert the necessary conventional inspection, with usage monitoring to adjust the repeat interval, is an appealing combination of approaches which is not unrealistic in the next decade".

4.2 Conclusions related to Terms of Reference

"1 Identify the areas in which Health Monitoring is likely to be a necessary or preferred means of achieving those airworthness objectives."

The work detailed in Appendices 3 and 4 identifies the following areas of the helicopter as those in which Health Monitoring is most likely to be the necessary or preferred means of achieving the airworthiness objectives:

- Transmissions including Gearboxes
- Rotor Systems
- Flight Control Systems
- Engines

"2 Establish the extent to which existing technology is capable of providing the required Health Monitoring."

Paragraph 3.3 of the report identifies, for each section of the helicopter, current technologies which could be applied more extensively to provide airworthiness and reliability benefits.

"3 Identify the areas where existing technology does not meet the need and suggest the timescale in which the shortfall should be made good."

The following list identifies items on which research and development should be encouraged (see also Attachment 1 to Appendix 4.

(i) Vibration Analysis: extension of existing capabilites for Transmissions, Rotor Systems, Flight Control Systems, Structure and Engines, in terms of algorithms, implementation, and correlation with condition.

(ii) Wear Debris Monitoring: extension of existing capabilities for Transmissions and Engine Oil Systems and Hydraulic Systems in terms of improving catch efficiency, implementation, and correlation with condition.

4 CONCLUSIONS (Cont'd)

4.2 (Cont'd)

(iii) Pressure temperature and flow sensors for lubrication system.

(iv) Optical Fibre Strain Detectors: Metal and Composite Rotor Blades, Rotor Hubs, Control Linkages, Primary load paths in Structural and Skeletal Gearbox Casings - fibres, bonding, connectors, signal processing, correlation with condition.

(v) Electrical resistance strain gauging and FM telemetry transmission for metal blades and hubs.

(vi) Optical sensors, data links and interfaces for 'Fly-by-Light' applications.

(vii) Improved accuracy and "intelligent" blade tracking facilities.

(viii) FM Telemetry Torquemeters provide a means of measuring mean torques with high accuracy and reliability. They also have a wide frequency bandwidth which could be used for diagnosing faults in shafts, gearboxes, engines and rotor systems.

(ix) 'At aircraft' detection of oil contamination (hydraulic fluids and lubricants) by particles of water.

(x) Application of Expert Systems technology to:-

(a) Development of algorithms - individual and combined Health Monitoring techniques, including trending of oil system parameters.

(b) Correlation of Health Monitoring system performance data.

(c) Evaluate logic in Health Monitoring system management and maintenance manuals.

(d) On-board Health Monitoring systems.

(xi) On-board Health Monitoring processor/interface/display development.

(xii) Ground-based Health and Usage Monitoring Data Management Systems.

(xiii) 'Smart' sensors - sensors with dedicated processing and control interfaces.

The timescales for such research and development activities must be such that the technology is available in time to match that of future helicopters which are designed to meet the revised airworthiness requirements referred to in this report.

5 RECOMMENDATIONS

5.1 Recommendations related to Terms of Reference

"4 Recommend the means by which additional technology should be researched and developed."

The Working Group found that most of the areas of technology required for Health Monitoring were already under development. In some areas, as detailed in para 4.2 of this report, further research and development is required, particularly relative to the application of these techniques to individual systems.

On this basis it is recommended that this report be sent to interested bodies such as the Science and Engineering Research Council, research and development organisations and universities concerned with this technology. This will also satisfy Recommendation 12 of the HARP report.

It is also recommended that such development of Health Monitoring techniques be undertaken on rig based or flight demonstrators such as the proposed Helicopter Avionics Flight Systems (HAFS) demonstrator and also by means of in-service trials with suitable helicopter operators.

"5 Advise on the principles that should apply to Airworthiness Requirements for Health Monitoring."

It is recommended that requirement changes are necessary to take account of, and encourage the use of, Health Monitoring Techniques. Furthermore, where credit is claimed for Health Monitoring in the safety assessment, specific airworthiness requirements should apply. The details of the recommended changes are covered in Section 3.5 and Appendix 5 of this report.

5.2 Other Recommendations

(i) Although the Terms of Reference of the Working Group refer to "Future Helicopters" the Group does not feel that this constraint should be taken as limiting its recommendation to new designs only. It is therefore most strongly recommended that the Health Monitoring Techniques are used as an aid to improved airworthiness on existing Helicopters which are likely to remain in service for an extended period.

Where relevant, this report covers the implications on both new designs and existing aircraft.

(ii) It is recommended that centrally promoted and sponsored health monitoring installations be carried out on in-service helicopters. This would be an effective means of demonstrating the benefits of health monitoring and catalysing interest in its application to existing helicopters.

(iii) Discussion/negotiation with other foreign Airworthiness Authorities and helicopter manufacturers on the need for, and implementation of, health monitoring techniques should take place, via the JAR, FAA and other suitable channels. Unless such liaison produces internationally agreed requirements, the time may arrive where foreign helicopters are not acceptable under UK airworthiness standards without suitable modification.

(iv) A Helicopter Health Monitoring Advisory Group should be set up to provide a stimulus for continued improvements in health and usage monitoring technology for helicopter applications. The objectives would be to:-

(a) increase awareness of problems - components and HUM systems.

(b) increase awareness of new solutions.

(c) influence research - funding and technical, if necessary providing a technical monitoring function or assistance to DTI, SERC, MOD, etc.

(d) improve operator commitment through manufacturer/operator dialogue.

(e) provide additional expert comment on draft airworthiness requirements circulated for comment (on HUM issues)

(f) provide a Helicopter Health Monitoring User Guide, providing sufficient detail on the systems currently in service and in development.

The Advisory Group should include representatives of Airframe, Engine, ESASC, MOD, operators and CAA. The group should liaise with MOD Advisory Groups.

(v) Manufacturers, Operators and Overhaul Agencies should co-operate in producing data banks correlating health monitoring indications with component condition on strip, in order to:

i) improve health monitoring technology

ii) improve airworthiness through improved feed-back to design.

(vi) Helicopter manufacturers, operators and overhaul agencies should identify responsibility for Health and Usage Monitoring activities within their airworthiness management structures.

(vii) Further work is needed to investigate available accident data to determine whether the advantages of health monitoring could be more widespread than established by this study.

APPENDIX 1

LIST OF MEMBERS OF HEALTH MONITORING WORKING GROUP

MAIN GROUP

Mr B L Perry	-	CAA (Chairman)
Mr R Ablett	-	CAA
Mr D Astridge	-	Westland Helicopters Ltd
Dr J W Bristow	-	CAA
Cdr M J D Brougham	-	MOD (PE)
Mr R H Casbard	-	CAA
Mr A T Dalton	-	CAA
Capt M Griffin	-	Bristow Helicopters Ltd
Mr M Leighton	-	CAA
Mr T G Morton	-	Rolls Royce Ltd
Mr M Ryland	-	ESASC
Mr M J Smith	-	CAA
Mr L P Winnert	-	British Airways Helicopters Ltd
Mr J E Witham	-	CAA (Secretary)

INDUSTRY SUB-GROUP

Mr D Astridge	-	Westland Helicopters Ltd (Chairman)
Cdr M Brougham	-	MOD (PE)
*Mr P Gadd	-	MOD (NAML)
Mr T Morton	-	Rolls Royce Ltd, Leavesden
Mr M Ryland	-	RACAL
*Mr R Freeman	-	Smiths Industries
*Mr I Stit	-	GEC Avionics Ltd
*Mr M Williams	-	Dowty Electronics Ltd
Mr L Winnert	-	British Airways Helicopters Ltd
Capt M Griffin	-	Bristow Helicopters Ltd

* Co-opted Members

APPENDIX 2

RELATED PAPERS AND REPORTS

1	Elliott C A	Condition Monitoring of Helicopter Machinery. Note to HARP. 30 September 1983.
2	Astridge D G Roe J D	Health and Usage Monitoring in Helicopters. Paper 38, Ninth European Rotorcraft and Powered Lift Forum, Stresa, Italy, September 1983.
3	Astridge D G Roe J D	The Health and Usage Monitoring System of the Westland 30 Series 300 Helicopter. Paper 81, Tenth European Rotorcraft Forum, The Hague, The Netherlands, August 1984.
4	Astridge D G	Health and Usage Monitoring System Developments in Helicopters. Symposium on Helicopter Airworthiness, Royal Aeronautical Society, London, December 1984.
5	Bristow Dr J W	Helicopter Structural Integrity in Relation to Airworthiness. Symposium on Helicopter Airworthiness, Royal Aeronautical Society, London, December 1984.
6	M Neale & Associates	A Guide to the Condition Monitoring of Machinery. HMSO 1979.
7	Tauber Dr T	AIR-1828-A Guide to Gas Turbine Engine Oil System Monitoring. SAE 831477, Aerospace Congress and Exposition, Long Beach California, October 1983.
8	Astridge D G	Advanced Gearbox Health Monitoring Techniques. International Journal of Aviation Safety, Volume 2, Number 2, September 1984. Reprint of article in Westland Journal 'Future', Winter 1983.
9	Cheeseman Prof I C	Condition Monitoring of Rotorcraft Dynamic Systems. Symposium on Helicopter Airworthiness, Royal Aeronautical Society, London, December 1984.
10	Report	Spindle Failure Cited in S76 Helicopter Crash in Scotland. Aviation Week and Space Technology. October 22 - November 1984.
11	Astridge D G	Application of Vibration Analysis to the Health Monitoring of High-Duty Gearboxes. PEMEC Design Engineering Conference, Birmingham, October 1981.
12	Tauber Dr T	Full Flow Debris Monitoring in Gas Turbine Engines. ASME 81-GT-60 March 1981.
13	Kincaid W S	A Computer Based Laboratory System for Condition Monitoring by Lubricant Analysis. Condition Monitoring 1984 U C Swansea.

14 Yarrow A & Gadd P — The Role of Ferrography in the Monitoring of Helicopter Assemblies. Condition Monitoring 1984. UC Swansea.

15 Bruce T, et al — Condition Monitoring of Scout/Wasp Helicopter Gearbox Fatigue Trials. Royal Aircraft Establishment TR 79079, July 1979.

16 Price A L, Roylance B J — The Rotary Particle Depositor. Condition Monitoring 1984. UC Swansea.

17 Smith J D — Transmission Error Measurements in Gearbox Development. Paper 33, AGARD Conference pre-print 369 Gears and Power Transmission Systems for Helicopters and Turboprops. Lisbon, August 1984.

18 Trade Brochure — Products for Aircraft, Industrial and Military Fluid Systems. Technical Development Company, December 1984.

19 Data Sheets — Hydrogen Monitoring Probes. Cormon Ltd 1984.

20 Freeman R F A et al — A Monitor for Abrasive Particles in Fluids. Fulmer Research Laboratories Ltd, 1984.

21 Tauber Dr T — An Instrument for Oil Wear Metal Analysis by X-Rays (OWAX). Technical Development Company 1984.

22 Price A L, Roylance B J — Use of Quantimet in Conjunction with Ferrography in Monitoring Helicopter Gearbox Systems. UC Swansea Report 80/425. April 1980.

23 McFadden P D, Smith J D — Acoustic Emission Transducers for the Vibration Monitoring of Bearings at Low Speeds. Proc. I Mech.E Vol 198C No. 8. 1984.

24 McFadden P D, Smith J D — Information from the Vibration of Rolling Bearings. Condition Monitoring 1984. UC Swansea.

25 Leszek W J — Water in Oil Analysis for Condition Monitoring. Condition Monitoring 1984. UC Swansea.

26 Norvelle F D — An Extra-Laboratory Method for the analysis of Particulate Contamination in Off Highway Vehicle Fluid Systems. Condition Monitoring 1984. UC Swansea.

27 Moreton G, Yardley E D — Use of Wear Debris Analysis to Monitor Gear Transmissions used Underground. Condition Monitoring 1984. UC Swansea.

28 Tauber Dr T E, Howard P L — QDM - A 'Smart' On-line Oil Debris Monitoring System. Condition Monitoring 1984. UC Swansea.

29 Mason R A — The Development, Proving, and Application of an On-line Metal Particle Detector. Condition Monitoring 1984. UC Swansea.

30 Bogue R W — An Improved Magnetic Plug for the Continuous Monitoring of Wear Debris. Condition Monitoring 1984. UC Swansea.

31 Harries C J et al — An On-line Ultrasonic Device for Monitoring Contamination in Fluids. Condition Monitoring 1984. UC Swansea.

32 Jarvis N L et al — Chemical Microsensors in Lubrication and Tribology. Condition Monitoring 1984. UC Swansea.

33 Koelsch W A — Fault Detection/Location System for Intermediate and Tail Rotor Gearboxes. American Helicopter Society Reprint RWP-17 Williamsburg, Va. November 1982.

34 CAA — Civil Aviation Authority, Airworthiness Notice 45, Software Management, Issue 1, November 1983.

35 CAA — Civil Aviation Authority, HARP Review of Helicopter Airworthiness, CAP 491, London June 1984.

36 Cardrick A W — A Strategy for the Fatigue Substantiation of Helicopter Dynamic Components. Symposium on Helicopter Airworthiness, Royal Aeronautical Society, London, December 1984.

37 Mathew J and Alfredson R J — The Condition Monitoring of Rolling Element Bearings Using Vibration Analysis. Journal of Vibration, Acoustics, Stress, and Reliability in Design, Vol 106, p 447, July 1984.

38 Trigg N E — Helicopter Health Monitoring. Journal of Noise Control and Vibration Isolation, March 1978. (Reprinted by Data Acquisition Ltd).

39 Sioshansi P — Surface Layer Activation Technique for Monitoring In-Situ Wear Measurement of Lubricated Systems. Proceedings of the Oil Analysis Workshop Symposium, Pensacola, Fl, May 1983.

40 Asher J et al — Thin Layer Activation, AERE, Harwell, Report R-10871 (1983).

41 — Ultrasonic Waveguide leads to all-in-one liquid monitor. Eureka Innovative Engineering Design, December 1984.

42 Stewart R M — Machinery Management based on the Application of Modern Diagnostics, Control Theory, and Artificial Intelligence. Condition Monitoring 1984 P.32 UC Swansea, April 1984.

43 Webber T C J — Monitoring the advance of Corrosion. Unit Inspection Company, Swansea 1982.

44 Dyer D and Stewart R M — Detection of Rolling Element Bearing Damage by Statistical Vibration Analaysis. Proc. Conf. On-line Surveillance and Monitoring of Process Plant, City University, London, September 1977.

45 Rotortuner — A Smoother Ride for Helicopters. Flight International, p 940, 13 October 1984.

46 Dolney L J and De Hoff R L — Maintenance Information Management Systems (MIMS) - Strategic Maintenance Decision Support. Condition Monitoring 84 P.17 UC Swansea. April 1984.

47 CAA — Condition Monitored Maintenance: an explanatory handbook. CAP 418 Civil Aviation Authority. July 1978.

48 Dalton A T — Rotorcraft - the application of Condition Monitoring. Rotorcraft Symposium, Royal Aeronautical Society, London. February 1980.

49 Clarke J E — Compliance of W30-300 with the HARP Review Recommendations. Symposium on Helicopter Airworthiness, Royal Aeronautical Society, London, December 1984.

50 Case R I and Andrews K — Design of the EH101 Helicopter for Safety and Performance. To be published at American Helicopter Society Meeting, Fort Worth, Texas, USA, May 1985.

51 Grainger P S — Helicopter Data Acquisition in WHL, Paper 12, AGARD Structure and Materials Panel Specialists Meeting, Sienna, Italy, April 1984.

52 Hunt T M & Tilley — Techniques for the Assessment of Contamination in Hydraulic Oils. Paper C244, I Mech.E Conference on Contamination Control in Hydraulic Systems, Bath, September 1984.

53 Leonard R A and Thomson B — Vibration and Stray Flux Monitoring for Unbalanced Supply and Inter-turn Winding Fault Diagnosis in Induction Motors. Paper 21 Condition Monitoring 1984, UC Swansea, April 1984.

54 Aldhouse G L P — United Kingdom Military Engine Monitoring Experience. AIAA-84-1409. 20th Joint Propulsion Conference, Cincinnati, June 1984.

55	Floyd M D	Engine/Airframe Health and Usage Monitoring - An Alternative Approach via Advanced Vibration Monitoring Systems. Society of Flight Test Engineers Symposium, St Louis, Mo, August 1984.
56	Perks M and Brammer P	Helicopter Engine Control Systems. 9th European Rotorcraft Forum, Stresa, Italy, September 1983.
57	Kearse A J and Rudman J	Radial Elastomeric bearings: Testing and Indications of Failure. Tribology International, P.249, October 1982.
58	Hovell & Webber	Operational Flight Data from a Helicopter in the Training Role. RAE Technical Report 78014, January 1978.
59	Wheeler P J and Essex N J	Concorde AIDS Powerplant Applications. Aircraft Engineering P.11 December 1978.
60	La Pierre L R	TEMS/CEMS An Advanced On-condition Maintenance Concept Undergoing Evaluation on the A-10/GE TF34-100. AIAA/SAE/ASME 20th Joint Propulsion Conference, Cincinnati, June 1984.
61	Board D B	Incipient Failure Detection in CH-47 Helicopter Transmissions. ASME 75-WA/DE-16, ASME Winter Meeting 1975.
62	George J A et al	Helicopter Bearing Failure Detection Utilising Shock Pulse Techniques. AIAA/SAE 13th Propulsion Conference, Orlande F I, July 1977.
63	Andrew M J	The diagnosis of Helicopter Main Rotor Faults Paper 33, Ninth European Rotorcraft Forum, Stresa, Italy, September 1983.
64		Engine Monitoring. Avionics Magazine (USA) February 1985.
65	Jones M H	An Assessment of Lubricant Analysis for Condition Monitoring of Gas Turbine and Diesel Engine Operation. JOAP Int. Symposium, Pensacola, Fl, USA, May 1983.
66	Tauber Dr T et al	Full Flow Debris Monitoring and Fine Filtration for Helicopter Propulsion Systems. American Helicopter Society Meeting - Rotary Wing Propulsion Systems, Paper RWP-24, Williamsburg, Va, USA. November 1982.
67	Stevens S C Major-General	Army Aviation Lube Systems - Time for a Change. US Army Aviation Digest, April 1983.

APPENDIX 3

SUMMARY OF CONCLUSIONS FROM SUB GROUP REPORTS

This Summary has been prepared from the five Sub-Groups' reports and has been arranged in a tabular form.

The first column lists the various Health Monitoring Techniques identified by the Sub-Groups. The second column indicates areas in which the techniques appear to be relevant and the third column lists components or items which might be amenable to suitable Health Monitoring methods. In some instances the third column refers only to a component and not a failure mode.

	TECHNIQUE	APPLICABLE AREA	RELEVANT FAILURES
1	VIBRATION MEASUREMENT & ANALYSIS	Gearboxes	Gear tooth cracking/chipping Gear web cracking Bearings Shafts Couplings Casings Clutches Mounts
		Transmission/ Rotor Shafts	Bearings Couplings Clutches
		Main Rotor Heads & Tail Rotor Heads	Hinges/Bearings Elastomeric bearings Flexural & torsional elements
		Dampers	Damping function
		Rotating Controls	Bearings
		Rotor Brakes	Bearings Shafts Couplings Disc
		Non Rotating Flying Controls	Bearings Shafts Couplings
		Engine	Bearings Blades Cracked discs
		Main Rotor Blades & Tail Rotor Blades	Spar cracking/delamination/ disbond Trailing edge
		Hubs	Bolts Splines Delamination/disbond/fracture
2	NOISE MEASUREMENT & ANALYSIS	Gearboxes	Gear tooth cracking/chipping Gear web cracking Bearings Clutches
		Transmission/ Rotor Shafts	Bearings Clutches
		Rotating Controls	Bearings (Swashplate)
		Rotor Brakes	Bearings

	TECHNIQUE	APPLICABLE AREA	RELEVANT FAILURES
3	AURAL	Gearboxes	Gear tooth cracking/chipping Gear web cracking
4	DETAILED VISUAL/ BORESCOPE INSP	Gearboxes	Gear tooth cracking/chipping Gear web cracking Shafts Couplings Casings Clutches Seals Mounts
		Shafts	Seals
		Main Rotor Head/ Tail Rotor Head	Droop Stops Elastomeric bearings
		Rotating Controls	Bearings
		Rotor Brake	Seals Disc
		Non-Rotating Flying Controls	Bearings Shafts Couplings
		Engine	As applicable
		Main Rotor Blade	Spar corrosion Disbond Lightning Strike Trailing edge Attachment bolts
5	DEBRIS COLLECTION & ANALYSIS	Gearboxes	Spline/shafts Bearings Shafts Couplings Seals Oil Pumps
		Transmission/ Rotor Shafts	Bearings Couplings Seals Oil Pumps
		Main Rotor Head & Tail Rotor Head	Bearings
		Dampers	Wear
		Rotating Controls	Bearings

	TECHNIQUE	APPLICABLE AREA	RELEVANT FAILURES
		Rotor Brakes	Bearings Shafts (Splines) Couplings Seals
		Hydraulic Systems	Fluid Sampling Wear
		Engine	Bearings Gears Seals Carbon
6	BACKLASH CHECKS	Gearboxes	Spline/shaft
		Rotor Brake	Shafts
		Non-Rotating Flying Controls	Drive mechanisms
7	LOCALISED TEMPERATURE MEASUREMENT	Gearboxes	Bearings Casings
		Shafts	Bearings
		Main Rotor Head & Tail Rotor Head	Bearings
		Rotating Controls	Bearings
		Rotor Brakes	Bearings
		Hydraulic Systems	Pumps Seals Couplings
		Engine	Gas path Bearings Casing temp. Bay temps. Elastomeric elements
8	VISUAL/NDT (IN-SITU)	Gearboxes	External couplings Casings Mounts
		Transmission & Rotor Shafts	Couplings
		Main Rotor Head & Tail Rotor Head	Structural elements Elastomeric bearings
		Dampers	Structural elements

	TECHNIQUE	APPLICABLE AREA	RELEVANT FAILURES
		Rotating Controls	Bearings Structural elements
		Rotor Brakes	Couplings
		Non-Rotating Flying Controls	Structural elements
		Engine	As applicable
		Main Rotor Blade	Spar cracking/corrosion/ delamination/disbond Root end & lugs Flexural/torsional elements (corrosion & fracture).
		Primary Structure	Cracks Wear Corrosion
9	OIL FLOW & POINT OF APPLICATION DETECTION	Gearbox	Lubrication
		Shafts	Lubrication
		Engine	Lubrication
10	FLUID PRESSURE, CONTENTS & TEMPERATURE MEASUREMENT	Gearboxes	Lubrication
		Shafts	Lubrication
		Hydraulic Systems	System deterioration
		Engine	Lubrication
		Main Rotor Head	Lubrication
11	EXTERNAL FLUID LEAKAGE DETECTION	Gearboxes	Lubrication
		Rotor/Transmission Shafts	Lubrication
		Dampers	Loss of fluid
		Hydraulic systems	System deterioration
		Engine	Lubrication
12	DIFFERENTIAL MOVEMENT DETECTION	Gearbox	Clutch Slippage
		Shafts	Clutch Slippage

	TECHNIQUE	APPLICABLE AREA	RELEVANT FAILURES
13	TRACKING	Main & Tail Rotor Head	Hinges Elastomeric bearings
		Main Rotor Blades	Spar & Trailing edge
14	CONTROL LOAD MEASUREMENTS	Main & Tail Rotor Head	Elastomeric bearings
		Rotating Controls	Bearings
		Non-Rotating Flying Controls	Bearings
15	BLADE LEAD LAG MEASUREMENT	Dampers	Loss of damping
16	SHOCK MEASUREMENT	Rotating Controls	Swashplate bearing
17	POWER ASSURANCE	Engine	Deterioration of relevant components such as gas path, fuel system.
18	CRACK DETECTION/ INDICATION	Main Rotor Blade	Spar cracks (metal & composite)
		Blade Root Ends & Lugs	Cracks
		Attachment Bolts	Cracks
		Rotor Head Hinge Pins & Bearings	Cracks
		Flexural & Torsional Elements	Cracks
		Hubs	Bolt cracks
		Primary structure	Cracks

APPENDIX 4

CAA HELICOPTER HEALTH MONITORING WORKING GROUP

REPORT OF THE INDUSTRY SUB-GROUP

HELICOPTER HEALTH MONITORING TECHNIQUES

CURRENT AND FUTURE

MARCH 1985

CONTENTS

ABBREVIATIONS

Accel	-	Accelerometers
ACT	-	Actived Control Technology
AFCS	-	Automatic Flight Control System
AGIC*	-	Active Gearbox Interface Control
BAe	-	British Aerospace
BAH	-	British Airways Helicopters
Bath U	-	Bath University
BB	-	Bleeding Bolts*
Bell	-	Bell Helicopters
BHL	-	Bristow Helicopters Ltd
BIM*	-	Blade Inspection Method
BITE	-	Built-in-test equipment
C	-	Checks (eg Visual, Manual, Torque wrench)
CGI	-	Cruise Guide Indicator
CH	-	Chadwick Helmuth
CI	-	Cockpit Instruments
CIT	-	Cranfield Institute of Technology
CU	-	Cambridge University
DE	-	Dowty Electronics
Dev	-	Development
DI	-	Data Interpretation Ltd., University of East Anglia
DJB	-	D J Birchall
DT	-	Damage Tolerance
Dup	-	Duplicated Systems
ECD	-	Electrical Chip Detector
EEL	-	EEL Ltd
Endv	-	Endevco
ESA	-	Enhanced Signal Averaging
FADEC	-	Full Authority Digitial Engine Control
FSpec	-	Frequency Spectra
FWA	-	Fixed Wing Aircraft
GE	-	General Electric Company of America
GSE	-	Ground Support Equipment
HF	-	High Frequency
HFE	-	High Frequency Enveloping
HHC	-	Higher Harmonic Control
HM	-	Health Monitoring
HSDE	-	Hawker Siddeley Dynamics Engineering
IBIS*	-	In-flight Blade Integrity System
IC	-	Imperial College, London
II	-	Inspection Instruments Ltd
ISIS*	-	Integral Spar Integrity System
LE	-	Leading Edge (Blade)
LEIGH	-	Leigh Instruments
LEM	-	Limit Exceedance Monitoring
LI	-	Litton Industries
LVDT	-	Linear Variable Differential Transformer
MCTH	-	Helitune Ltd
MGB	-	Main Rotor Gearbox
MOD	-	Ministry of Defence
MP	-	Magnetic Plug or Chip Collector
MPFL	-	Multi-Parameter Fatigue Lifing
MVC	-	Muirhead Vactric Components

N/A	- Not applicable
NAML	- Naval Air Materials Laboratory
NDI	- Non-destructive Inspection
NGL	- Normalair Garrett Ltd
NMI	- National Maritime Institute
NR	- Main Rotor Blade passing frequency (1R = rotor order)
NT	- Tail Rotor Blade passing frequency (1T = rotor order)
OWAX	- Oil Wear Metal Analysis by X-Rays
Pl	- Plessey
PM	- Performance Monitoring
PPI	- Power Performance Index
QDM*	- Quantitative Debris Monitor
RAN	- Royal Australian Navy
RAE	- Royal Aircraft Establishment
Rec	- Recording
RR	- Rolls Royce Ltd
Sacr	- Sacrificial Strip
Self	- Self sufficient - ie not dependent on additional checks
SHL	- Stewart Hughes Ltd
SI	- Smiths Industries
ShU	- Sheffield University
SL	- Safe Life
SM	- Status Monitoring
SOA	- Spectrometric Oil Analysis
SPM*	- Shock Pulse Monitoring
SRFMT	- Short Range Frequency Modulated Telemetry
STC	- Standard Telephone Co
StnU	- Southampton University
Taxi	- Rotor head moment monitoring/display during ground taxi
TBO	- Time between Overhaul
TC	- Thermal Controls Ltd
TE	- Blade trailing edge
TDC	- Technical Development Company (TEDECO)
TGB	- Tail rotor gearbox
TOLS	- Take-off and landing cycles
TLA*	- Thin Layer Activation
UCS	- University College, Swansea
UM	- Usage Monitoring
VCL	- Vibration Check List
Vibn	- Vibration monitoring/analysis
V-M	- Vibro-Meter SA, Switzerland
WATOG	- World Airlines Technical Operations Glossary
WHL	- Westland Helicopters Ltd

* Registered Trade Marks or Patented Systems

CAA HELICOPTER HEALTH MONITORING WORKING GROUP
REPORT OF THE INDUSTRY SUB-GROUP
MARCH 1985

1. OBJECTIVE

The terms of reference of the industry sub-group are appended in Figure 1 - essentially t.o.r 2 and 3 of the main working group. It was clear that, in the limited time available, an exhaustive survey would not be possible, but it was determined to:-

i) List some of the health monitoring techniques currently applied to flight critical components.

ii) List some techniques/topics which clearly justify research effort.

iii) Add general points considered to be important in specifying or implementing health monitoring systems.

iv) Produce tentative lists of characteristics required of health monitoring facilities for each component considered.

v) Produce some detailed analysis in a format designed to contain all the information required in the terms of reference, and in a form which could be readily extended as time permits.

vi) Attempt an estimate of overall feasibility in terms of possible implementation date, in the appended detailed analysis sheets. This to account for all aspects listed in item B of the terms of reference.

2. MEMBERSHIP

Industry representatives on the main working group co-opted four additional members as indicated in Appendix 1 to the main group report.

3. INVESTIGATION PROCEDURE

The routes followed to arrive at priority ordered lists of in-service health monitoring methods and research topics is indicated in Figure 2. Activities above the dotted line are those addressed by the component sub-groups of the main committee relative to the first of the terms of reference - identifying critical areas for which effective health monitoring can improve airworthiness (summarised in Appendix 3) to the main group report. To assess effectiveness it was seen to be necessary to review HM system requirements for each componenet, and, in addition to discussing specific methods, to review more general issues such as system implementation, the influence of engineering improvements to the components being monitored, certification issues, etc. Detailed discussion of effectiveness of individual HM methods is therefore beyond the scope of this limited study, and an indication is given on a Scale 1-3 (good to poor). In an attempt to make best use of discussion time the analysis proforma was circulated to each member for contributions outside the meetings, and published review papers used where available.

This report lists the general comments, summary lists of HM methods known to be in service, and areas requiring further research, for each major component. The components were considered in order of predicted safety criticality/amenability to health monitoring of future helicopters. A study of accident/failure data may indicate a different order of priorities for current/past helicopters. The analysis sheets are attached at Appendix 2.

4. REVIEW PAPERS

References 1-4* are concerned with health and usage monitoring of the complete helicopter, reference 1 representing an 'outsiders view' resulting from a brief study involving discussions with 'practitioners'. References 2-3 reflect the commitment of Westland Helicopters Ltd to health and usage monitoring, together with their policy and experience in implementing traditional and advanced techniques. Reference 4 was prepared at short notice for the recent conference on Helicopter Airworthiness at the Royal Aeronautical Society and was intended to summarise the data presented to the main committee at the meeting held in Yeovil on 5 April 1984. Reference 38 addresses health monitoring of helicopter transmissions, rotors and rotating components in general (vibration analysis). Reference 5, whilst primarily concerned with helicopter structure, contains an up to date review of airworthiness requirements, fatigue and static strength substantiation, and lists the contributory causes of 35 significant fatigue or mechnaical failure events that have occurred since 1981. Reference 6 provides a fairly detailed review of mechanical health monitoring techniques in general application. Reference 7 summarises a guide produced by the SAE E-32 Committee and provides a very useful survey of HM methods applicable to oil systems in engines and helicopter transmissions. Reference 8 takes this further for helicopter transmissions with comments on the performance of traditional and more advanced techniques. Reference 9 discusses the operating characteristics of rotor systems, describes the development of an optical blade tracking system which can provide accurate positional data in height and azimuth, and describes developments in machinery management techniques at Systems Control Technology and Stewart Hughes Ltd. Reference 15 summarises the results of several HM techniques applied to a gearbox fatigue test programme. Most of the remaining references concern specific techniques or products.

5. TERMINOLOGY

5.1 HM Techniques: Primary categories such as vibration analysis, wear debris assessment, etc.

5.2 HM Methods: Sub-division of 'techniques' such as frequency spectra, and time signal averaging for vibration analysis.

5.3 Health Monitoring: Whilst the terms of reference specify 'health' monitoring techniques, it was not considered profitable to distinguish between health monitoring, inspection aids, performance, usage, and status monitoring etc in completing the analysis sheets - useful contributions to airworthiness should not be neglected in attempting to satisfy classification issues.

* All references in this sub-group report refer to Appendix 2 to the main group report.

We have therefore endeavoured to include any activity which permits advanced warning of unserviceability - this may involve visual or other inspection methods applied to the component, or analysis of manifestations of degradation such as wear debris transported by contacting fluids, or changes in physical characteristics such as temperature or vibration. The methods employed must be capable of having component rejection limits clearly defined, and these limits capable of establishment without prejudicing flight safety.

The term 'Health Monitoring' is used in preference to 'Condition Monitoring' to prevent confusion with 'WATOG' terminology where 'Condition Monitored Maintenance' relates to analysis of operating experience information - it is not a preventive maintenance process (ref 47, 48).

5.4 Alert/Diagnostic: The effectiveness of a health monitoring technique should be judged both for its alert and diagnostic capability. A major component can be rejected before it prejudices flight safety on the basis of a general indication of unserviceability, but the ability to isolate the individual component affected adds to the confidence of the rejection criterion and aids corroboration by inspection.

5.5 Health Monitoring Indications: There are three possible indications:-

i) Justifiable maintenance action (not necessarily immediate)
ii) False indication - action not justified.
iii) Failure to indicate a rejectable condition.

All three have airworthiness implications, even (ii) - cases are known where the health monitoring indicator is always ignored because it exhibits high incidence of false warnings.

6. CRITICAL AREAS WHERE AIRWORTHINESS CAN BE IMPROVED BY HEALTH MONITORING t.o.r.1

6.1 The alternative approaches by which a designer can treat individual components in order to meet airworthiness targets, and the relevance of different forms of monitoring (health, usage, performance, status) are discussed in Reference 4 (Figure 2 of Reference 4). Whether components are designed on a safe-life basis, fail-safe, or systems are duplicated, effective health monitoring can contribute to improvement of airworthiness. There is little evidence to suggest that random faults and overloads will be completely eliminated by advancement of component technology. The primary means of controlling airworthiness of a component is indicated in the analysis sheets, but the analysis is continued for any health monitoring technique that can contribute. Guidance on primary means of airworthiness control was given by some of the sub-groups addressing t.o.r.1.

6.2 It is worth bearing in mind the difference between designing to fail-safe or damage tolerant principles, and achieving certification on that basis. Health and usage monitoring may be particularly useful to components initially cleared on a safe-life basis, but later accepted as fail-safe. The certification processes for the two approaches are detailed in Reference 5.

6.3 For some components cleared for 'on-condition' removal, health monitoring techniques may provide the preferred means of airworthiness control - the integrity of the monitoring system and rejection criteria are particularly critical in this case.

6.4 Usage, or load exposure monitoring offers significant benefits to airworthiness in addition to savings in operating costs. One of the problems identified in the HARP report (Ref. 35) relates to inadequate prediction of operating loads when simulating service conditions in certification tests. There is evidence to suggest that unforeseen elevated stresses are a more serious threat to structural integrity than increases in frequency of usage, or the occurrence of abnormal manufacturing defect (Ref. 36).

Load exposure monitoring and limit exceedance monitoring can flag up incidence of such exceedances and invoke special inspections, shortened data sampling intervals, or modification of declared safe lives.

6.5 Flight critical components for which effective health monitoring would contribute to improved airworthiness include:-

.Transmissions

Primary: (criticality)	main torque path gears, bearings and support structure, oil systems; attachment and main load path structure; freewheels; tail drive shaft and support bearings, rotor brakes - disengaged in flight.

.Rotor Systems

Primary:	Blade attachments, hubs, rotating controls; anti-icing systems.
Secondary:	Dampers

.Flight Control Systems

Primary:	All components in powered controls, AFCS, ACT, HHC.
Secondary:	Electrical and hydraulic power supplies.

.Engines

Primary:	Rotor integrity, casing integrity, attachments, power assurance.
Secondary:	All major components, oil systems, accessory drives, and fuel control systems.

.Fuel Systems

Primary:	Fires, total engine failures.

.Cockpit Instruments,	Warning systems and integrated navigation systems.

6.6 Flight critical components for which health monitoring (other than inspection aids) appears to have limited potential include:-

- Air Data Sensors
- Airframe Primary Structure
- Undercarriages

6.7 Components which are not classified as flight critical but can benefit from health monitoring include:-

- Health and Usage Monitoring Systems (Built-in-Test) - not despatch critical.
- Navigation and Communication aids. (Built-in-Test)
- Environmental Control Systems (leakage from combustion heaters constitutes a serious airworthiness risk).

6.8 Health and Usage Monitoring of service aircraft is particularly important at high times - when approaching declared lives, and in extended life regimes, especially if coupled with higher severity operations.

6.9 In addition to monitoring components on service aircraft, airworthiness benefits accrue from (Ref. 4, Fig. 18):-

- Application of HM techniques in production quality assurance tests on components and aircraft.
- Application of HM techniques to development and certification tests on components and aircraft.
- Feedback of HM data from service, production, and development sources to design.

7. HEALTH MONITORING TECHNIQUES - GENERAL ISSUES

7.1 The summary of conclusions of the five sub-group reports addressing t.o.r.1 is attached as Appendix 3 to the main group report. The summary is useful in some respects, but as far as t.o.r's 2 and 3 are concerned the criticality of the component and failure mode are important; also methods/algorithms appropriate to different components may differ widely within a given technique (eg vibration analysis). Nevertheless the summary indicates the importance of:-

- Vibration analysis
- Wear debris monitoring
- Visual inspection aids

The Industry Sub-group has reservations about the practicality of noise measurement. Monitoring trends in system temperatures, pressures, flows, etc could be useful but requires accurate sensors and added intelligence either provided locally ('smart sensors') or by a centralised on-board processor. Adding such tasks to aircrew workload could jeopardise airworthiness.

7.2 For health monitoring provisions to be effective, full commitment by operators is necessary. This could be influenced by incentives in terms of significant increase in TBO/on-condition, etc.

7.3 Health monitoring system technology is developing at a rapid rate relative to helicopter life cycles, and retro-fit capability is of value. Successful examples of this are described in Reference 8.

Retro-fit application may not result in optimum systems in terms of performance or reliability, but will nevertheless contribute to improved airworthiness.

7.4 In new helicopter projects or major component modifications, provision for health monitoring facilities should be made at the initial design scheming stage. Whenever technology improvements are introduced consideration should be given to their impact on the health monitoring methods used (eg the influence of fine filtration on oil analysis methods, or the consequence of adoption of higher strength, less fracture-tough steels for vibration analysis or wear debris monitoring techniques). HM selection strategy should be based on Failure Modes and Effects Analyses.

7.5 Performance assessment of health monitoring techniques requires application to component tests to failure (seeded faults or accelerated conditions, provided failure modes and manifestations are representative); flight tests throughout the normal aircraft certification programme; and possibly also special flight programmes following certification.

7.6 HM installations should have high reliability and maintainability. The installation should not hazard airworthiness of the component to which it is fitted. Environmental testing of HM sensors should reproduce the characteristics of all appropriate factors measured at each sensor location, rather than relying upon general test requirements. This is particularly important relative to vibration and shock characteristics (less so for vibration sensors), and temperature (especially sensors with integral electronics components).

7.7 System response times should be compatible with degradation rate of subject components.

7.8 On-board monitoring/analysis systems provide greater protection against unforeseen failure modes (eg incident in ref. 10) than ground based data sampling systems. They permit faster response, data sampling at higher load conditions where detectability may be greater, and cockpit indications of 'need-to-know' arisings, plus the possibility of 'what-to-do' indications (Ref. 4). Data sampling/analysis with an on-board system can be continuous or 'snap-shots' triggered manually or automatically. Processing of recorded data can impose an unacceptable burden on some operators. The need for any recorded data should therefore be justified and an efficient means of processing that data should be visible. Maintenance data management systems are beyond the scope of this study but recent developments are encouraging (eg Refs. 42, 46).

Health monitoring developments should not be totally constrained by on-board implementation aims - it is conceivable that some problems could be controlled by techniques/algorithms that are inappropriate for on-board implementation.

7.9 Serious faults occurring in flight tend to be heard or felt by aircrew. Fast, accurate indication of the component at fault is required to aid pilot decision. This is only obtainable by an effective on-board system. Symptoms can be alleviated by adjustments elsewhere (especially by tuning rotor track or balance), disguising the real fault which may then progress to failure and loss of the aircraft. Improved diagnostic information available directly after flight minimise risks attendant on flights to test corrective action.

7.10 In-flight indications should be restricted to 'need-to-know' information relevant to the current flight. Between flight maintenance information should be displayed to ground crews. Reliance upon off-aircraft analysis of health monitoring data should be minimised. For techniques requiring off-aircraft analysis, the consistency in analysis, advanced warning capability and sampling intervals should be such that airworthiness is not compromised.

7.11 Consideration should be given to the requirements for validation of algorithms/techniques, mission criticality and software criticality of on-board and ground based HM systems.

7.12 Helicopter manufacturers and operators should be encouraged to set up HM data banks containing:-

i) component degradation modes and manifestations for given modification states and operations.

ii) HM system operation and reliability.

iii) Correlation of component condition with HM outputs.

7.13 Whilst currently available HM systems and research requirements can be surveyed, the intermediate category of systems under development may be somewhat restricted by commercial confidentiality.

7.14 Full assessment of health monitoring techniques is naturally limited by reticence on the manufacturers part to volunteer details of component failures for public scrutiny and awareness. Airworthiness authorities may be in a better position therefore to correlate the HM experience of different manufacturers and to pursue this aspect in accident investigations.

7.15 Health Monitoring software in on-board systems should be 'critical' category as defined by CAA Airworthiness Notice 45 (Ref. 34). Whether a specific item of HM hardware should be included in Minimum Equipment List should be a matter for discussion with the airworthiness authority.

7.16 Consideration needs to be given to the application and certification of 'Expert Systems' or learning system technology implemented (a) in ground support equipment specified in maintenance manuals and (b) in on-board systems.

7.17 The health monitoring of duplicated systems whilst in the dormant condition appears impractical - design/maintenance provisions should be made to permit regular exercising of such systems to ensure availability in the event of failure of parallel systems, and facilitate health monitoring. HM of duplicated systems is considered to be important, noting the relatively high incidence of instant or premature failure of alternate systems.

7.18 Cost and weight implications of health monitoring systems also require careful consideration. In this survey (Attachment 1) an estimate of overall feasibility is given in terms of possible implementation date. Factors considered in this were HM performance, reliability, cost, weight, workload, response time, compatibility, and justification (need). Techniques likely to be more costly than others are those requiring special-to-type sensors, sensor systems requiring removal of aircraft components to the sensor manufacturer for mounting, or otherwise necessitating incorporation during the manufacturing stage. In-service calibration can lead to operational cost penalties. The biggest potential cost driver of all is any requirement for special rig tests or dedicated aircraft flying for development and certification of a system. Cost, weight, and reliability implications tend to be more favourable in new component applications than in existing components where modification is necessary. Also cost benefits tend to be greater for new design components because of the benefits of the health monitoring systems to development testing, production quality assurance, and accelerated TBO growth. HM hardware and software modification costs can also be very significant.

7.19 Research effort is particularly worthwhile in techniques/sensors capable of diagnosing a wide range of faults (eg vibration analysis). Flexibility is required in order to provide rapid HM solutions to problems requiring longer term design modifications. Guide lines should be framed relative to research requirements, but this is beyond the scope of this current study.

8. TRANSMISSIONS

8.1 General

8.1.1 There is some scope for damage tolerance in gearbox design, provided by the gear configuration selected (Reference 4) - this can influence the number of components in the critical load path of a twin engined helicopter, and the secondary damage that can develop from an isolated primary defect. However, it is considered unlikely that damage tolerance could be the primary method of airworthiness control for transmissions for some time to come, hence the need for continued control by safe-life procedures aided by:-

i) Vital Parts Control Procedures

ii) Torque exposure monitoring as a better basis for fatigue life assessment than flying hours.

iii) Automated torque limit exceedance monitoring as a safer means of detecting overload on the many load sensitive components.

iv) Effective Health Monitoring Provisions.

v) Enhanced visual inspection aids and NDI facilities.

vi) Higher standard of build cleanliness - aids wear particle detection systems in addition to improving life of oil-wetted components.

vii) Wider use of oils better suited to transmissions, rather than use of engine lubricants for logistics reasons. Better tolerance to unforeseen excursions in conditions/ environment, and reduced wear debris generation generally.

8.1.2 Experience shows that a single health monitoring technique cannot satisfy all requirements.

8.1.3 The wide variation in gearbox configurations, casing structures, design practices generally, means that a health monitoring method that works well in one gearbox may not succeed or be necessary in another.

8.1.4 Analysis of wear modes and damage progression in gears, manifestations and appropriate detection methods are discussed in Ref. 11 - See also Ref. 4, Fig. 4.

8.1.5 Performance evaluation of several different health monitoring techniques have been carried out at Westland with tests to deliberate failure of W30 gearboxes, and fatigue substantiation trials of Scout/Wasp gearboxes (Ref. 15).

8.2 Health Monitoring System Requirements

8.2.1 Requirements for health monitoring of gearbox internals are discussed in Refs. 4 and 8. Summarising:-

i) Advanced warning of failure modes or potential defects.

ii) Clear rejection signal for wear modes.

iii) Clear rejection signal for fracture modes.

iv) In-situ visual inspection aids for confirmation of (ii) and for corrosion. (NB (iii) should be more sensitive than (iv) for cracks).

Item (i) may be primarily concerned with economic considerations, but clearly there are airworthiness benefits to earliest possible detection and trend monitoring of wear modes.

8.2.2 Health monitoring activities involving removal of oil samples, filters, or sensors from oil systems, or insertion of inspection equipment into gearboxes, should be closely controlled for:-

(a) integrity of the oil system and gearbox;

(b) consistency in health monitoring interpretation;

(c) implementation of appropriate action.

8.2.3 Health monitoring activities involving laboratory analysis of samples or data should be closely controlled for:-

(a) response time;

(b) consistency in all processes;

(c) clarity of recommendation.

8.2.4 Additional general requirements for oil system monitoring (includes oil-wetted parts) are discussed in Ref. 7. those relating particularly to airworthiness considerations include:

. debris transport within the oil system.
. fault isolation.
. rejection criteria.
. human factors.
. documentation and training.
. oil consumption and replenishment.

Naval Air Materials Laboratory experience suggests that wear debris assessment is required in two size ranges: 200 microns+ and 2-20 microns. For early warning of wear modes, magnitudes of iron wear particles in the size range 5-15 microns, and other metals in the range 2-10 microns are required. Such particles can be obtained by oil sampling techniques and are appropriate for laboratory analysis.

The generalised characteristics of debris size distributions relating to wear initiation and development in gas turbine engines, and those of analysis systems are discussed in refs. 12 and 65.

8.2.5 In addition to wear debris monitoring, oil system monitoring should be concerned with oil system operation and, to an extent, oil condition, including contamination. (Ref. 7).

8.2.6 Wear debris monitoring techniques should be capable of detecting wear in:-

. major components such as gears splines, shafts, and bearings (currently Ferrous materials).

- important components such as bearing cages (frequently cuprous), interface platings (Cu and Ag), hubs (sometimes Titanium), locking washers (Al), casing rubs (Mg or Al), Seals (cast iron, rubber, carbon), and plain bearings where fitted (Sn, Pb, Cu).

8.2.7 Additional requirements for on-line debris monitoring systems include:-

- high catch efficiency - sensors in sump, or exposed to full oil flow.
- debris retention - for examination (ease of removal), and pump protection.
- effective self-sealing housing.
- minimum particle size threshold(s).
- remote indication - frequent removal of collectors represents airworthiness hazard.
- quantitative output in maintenance bay.
- cockpit warnings undesirable. (Refs. 4, 66, 67).
- simple built-in test.
- interface capability to on-board processor.
- should not generate or suffer from EMC problems and should be immune to the vibration, shock, and temperature environment.
- trending capability

8.2.8 Additional requirements for vibration monitoring systems (see Ref. 11) include:-

- sensors on casings - accessible.
- sufficient sensors to isolate faults in identical components (especially upstream of power combining stage).
- analysis results should be expressible in quantitative terms.
- Appropriate setting of torque levels during monitoring.
- Software should be fully documented and controlled by procedures consistent with design control procedures.

8.2.9 Usage monitoring (torque for gears and bearings, rotor loads in addition for some casings) has a significant contribution to make to improved airworthiness. This requires continuous monitoring and preferably continuous on-board analysis.

8.3 Current Health Monitoring Systems - Summary

Details of systems known to be installed on production helicopters are listed in Appendix 2. Relevant review papers are Refs. 4, 6, 7, 8. A summary list is extracted:-

8.3.1 On-line Methods (Cockpit Warning Capability)

i) oil temperature and pressure indicators/warnings.

ii) electric chip detector (Ref. 18)

iii) Pulsed electric chip detector (+counters). (Ref. 18)

iv) Quantitative Debris Monitor (TEDECO). (Refs. 18, 28)

v) Vibration analysis - spectral methods (AH - 64A) (Ref. 33)

vi) Indicating Screens (CH47D)

vii) Pilot perceived noise is a source of gearbox rejections, sometimes incorrectly identified.

viii) Strain-gauge torquemeters of various types on tail rotor drive shafts (eg Scout, Wasp, Wessex - EEL).

The QDM (iv) has advantages described in Ref. 4 (Fig. 8). The ECD (ii) is prone to spurious indications except where good build cleanliness and/or fine filtration is used.

8.3.2 At Aircraft Inspection Methods (Installed, carry-on, or ground support equipment)

i) Magnetic chip collectors. (Ref. 18)

ii) Full flow debris monitoring screens. (Ref. 18)

iii) Filter blockages/impending blockage indicators.

iv) Borescope + guide tubes (tooth mesh patterns + wear). (Ref.8)

v) Oil level sight gauges, prismatics, and other level measurement techniques (Ref. 18) (cracked casings, oil lines, or leaking seals).

vi) (i) Can be supplemented with quantifying devices such as the Debris Tester (Inspection Instruments) where debris quantities are relatively high. (Ref. 27)

vii) Vibration analysis-frequency spectra (eg Ref. 38), and high frequency resonance (Refs. 61, 62).

8.3.3 Off-Aircraft Inspection Methods

i) Vibration analysis - enhanced signal averaging (W30).

ii) Spectrometric oil analysis.

iii) Ferrography - Direct Reading and Analytical

iv) Filter wash inspection.

Successes with (i) are described in Refs. 2, 3, 4 and 8, which also comment on the limitations of (ii) and (iii) and describes development activity to perform (i) on-board. Reviews of other vibration analysis techniques and capabilities are given in Refs. 6, 9 and 37. Useful papers describing implementation of oil analysis techniques are referenced at 13 and 14. Methods (ii), (iii) and (iv) are sometimes supplemented with the Scanning Electron Microscope with energy dispersive X-Ray microprobe to identify materials precisely (eg bearing steel rather than gear or shaft steels).

8.3.4 Additional Methods used in Development Tests

Thermal imaging is used successfully in development work aimed at reducing oil or metal temperatures (Westland).

A wide range of vibration analysis techniques are used during gearbox development work (Westland). A 'Quantimet' computer image analysing system has been used to supplement analytical Ferrography on helicopter gearbox development tests (UC Swansea). (Ref. 22)

A rack mounted QDM signal conditioner and display console is available for test cell use. (Ref. 18)

Theodolites have been mounted on gear shafts for measuring Transmission Error characteristics. Speckle Pattern Holography has been used for identification of vibration mode shapes in curing vibration induced failures.

8.4 Health Monitoring System Development - Summary

8.4.1 The capability of on-line monitoring systems is being greatly enhanced by the development of on-board processors interfacing cockpit visual display units and portable data transfer devices. The system under development for the W30-300 will include vibration analysis and QDM data processing (Ref. 3) (the latter is now available on a microchip). (Ref. 28)

8.4.2 Further developments of many of the systems described in 8.3 are in hand. In addition the following are in development (or available for application to helicopter transmissions):-

8.4.2.1 On-Line Methods:

- Vibration on board processor (W30). (Ref. 3)
- Shock Pulse meter.
- Inductive coil. (Ref. 29)
- On-line Ferrograph.
- Capacitative debris monitor.
- Remote level sensors (reed/float, capacitative, electro-optic, ultrasonic wave-guide) (Refs. 18, 41).
- Ultrasonic particle detector (IC)
- Oil temperature and pressure

8.4.2.2 At aircraft inspection Methods:

- . Vibration analysis - portable analyser (W30)
- . Comparator patch test. (Ref. 26)
- . Water in oil detector (IC)

8.4.2.3 Off aircraft Inspection Methods:-

- . Rotary Particle Depositor and Quantifier (Ref. 16)
- . Debris Tester development
- . X-ray fluorescent monitor (Ref. 21)
- . Colorimetric oil analysis.
- . Water in oil analysis. (Ref. 25)

8.4.2.4 Component Development Aids:-

- . Abrasivity monitor (Ref. 20)
- . Radioactive tagging (TLA) for wear and corrosion. (Refs. 39, 40).

8.5 Health Monitoring Research Requirements

8.5.1 Outstanding problem areas requiring algorithm/system development:-

- . Material defects - NDI - Forgings.
- . Corrosion - internal components and casings.
- . Contamination - particulates and water.
- . Distribution of load in planetary gears.
- . Casing fracture.
- . Continued development of vibration and wear debris monitoring.
- . Sensor development, cost and reliability.
- . Influence of environment on HM signals.

8.5.2 Scope of future technology:-

- . optical sensors for 'fly-by-light' helicopters
- . optical fibres/strain sensors for skeletal frame designs
- . 'smart' sensors - temperature, pressure, torque, vibration, with dedicated processing and control interfaces.
- . total on-board monitoring/maintenance systems - computer based flight and maintenance manuals.
- . use of Expert Systems to aid development of above.

9. ROTOR SYSTEMS

This section covers rotor blades, hubs, dampers, rotating anti-vibration features, and rotating control systems. Review Papers - refs 4, 5, 9, 36, 38, 63.

9.1 General

The airworthiness of current rotor systems is controlled by safe life procedures, aided by health monitoring, NDI facilities, ground inspection (visual/manual/torque checks), and pilot reported exceedances of torque and RPM limits, impacts etc. New rotor head and blade designs make increasing use of fibre composite materials which exhibit markedly slower fracture propagation rates than metal components, and different modes of degradation (delamination, disbonds, water up-take etc.) enabling a damage tolerant approach to be taken in design. Replacement of rolling element bearings by elastomeric bearings leads to a reduced number of moving elements, but variability in degradation remains a problem.

Bearingless rotors offer further enhancement in damage tolerance, but Higher Harmonic Control whilst reducing vibration levels in the airframe could place higher demands on the rotating control system components. Improved vibration control offers airworthiness benefits, and methods contributing to maintenance of factory clearance levels can be considered to be health monitoring. 'Multi-Parameter Lifing' (Ref. 4) proposals should reduce problems stemming from incorrect assumptions about operating spectra in safe-life demonstrations, but this places much of the airworthiness burden on the operator, whose task could be eased with on-board usage (simple parameter) monitoring systems. There remains, however, considerable scope for enhanced health monitoring systems, NDI techniques, and comprehensive usage monitoring in view of the potentially damaging effects of unanticipated loads (Refs. 5, 36).

9.2 HM System Requirements

9.2.1 Fracture propagation rates can be very high therefore an on-board detection capability with an ALERT warning to the pilot is advantageous. There is scope for ground-based or portable carry-on equipment for diagnosis of faults. It is unlikely that remote analysis of recorded data can provide sufficiently rapid response.

9.2.2 Effective, reliable means of signal transmission from rotating components to the structure are required, whether electrical, optical or other means of transmission.

9.2.3 Rotor 'tuning' facilities are used (blade track, rotor balance, vibration absorbers) to minimise rotor induced vibration in the structure (1R and NR frequencies) arising from manufacturing tolerances. It is necessary for health monitoring diagnostic systems to be capable of discriminating between the effect of manufacturing tolerances and abnormalities which could become serious defects. Alternatively this can be achieved by alert systems followed by effective NDI and ground check procedures.

9.2.4 'Re-blading' of current helicopters with blades in fibre composite materials, advanced sections and plan-forms is an activity providing opportunities for introduction of health monitoring facilities ab-initio. The extended fatigue lives offered by such blades relative to metal ones should not be jeopardised by unreliability in monitoring provisions. It is not clear, for example, whether optical fibre 'crack detectors' incorporated in the lay-up of composite blades offer improved airworthiness overall.

9.3 Summary of Current Health Monitoring Methods for Rotor Systems

Details of systems known to be installed on production helicopters are listed in Appendix 2.

9.3.1 On-Line Methods (Cockpit Warnings)

i) A cockpit indicating version of the blade spar pressure-leak system (eg IBIS) is in operational use.

ii) Perceived vibration is the most common source of rotor system fault alerts. Unfortunately subsequent ground checks do not always identify the fault and corrective action or adjustments can improve the symptoms but allow the fault to progress to failure.

iii) Signal transfer systems in use include slip-rings (unreliable), inductive, rolling contact, and radio-active systems.

iv) Ice accretion detectors - important to differentiate between ice and faults.

9.3.2 At - Aircraft Inspection Methods (Installed, Carry-on or Ground Support Equipment)

i) Blade spar pressure - leak indications (eg BIM, ISIS).

ii) Vibration monitoring using portable analysers producing frequency spectra (eg ref 38) - hence amplitudes at blade passing frequencies, structural natural frequencies, and gear meshing frequencies. Used in conjunction with Vibration Check List (NR) and Vibration Order Sheets.

iii) Rotor balancing equipment (eg ref 38) for those rotors for which balance corrections are appropriate. Used in conjunction with Vibration Check List (1R).

iv) Rotor blade tracking equipment (eg ref. 38).

In flight blade track and tab adjustment provisions are available on some helicopters.

v) Fracture of hollow bolts:- pressure - leak (Schraeder valve), or dye-penetrant ('Bleeding Bolts').

vi) Oil reservoirs - seal damage/wear.

vii) 'Bonk-meters' specifically designed for checking the natural frequency of vibration absorbers (eg. W30).

9.3.3 Off Aircraft Analysis Methods

i) Vibration monitoring - analysis of recorded data for comparison with Vibration Order Sheets, and implementation of Check List procedures when rotor or blade passing orders are out of limits; also defects in control linkages.

ii) Mechanical strain recorders (Leigh Instruments).

9.3.4 Additional Methods used in Development Tests

i) Strain gauges.

ii) SFRM Telemetry Torquemeters (Ref. 3).

iii) Comprehensive digital recording and analysis facilities (Ref. 51).

iv) Long range telemetry from aircraft to ground stations.

9.4 Rotor System Health Monitoring Developments - Summary

9.4.1 The capability of on-line monitoring systems is being greatly enhanced by the development of on-board processors interfacing cockpit visual display units and portable data transfer devices. The system under development for the W30-300 will include analysis of strain-gauge, torquemeter, and accelerometer signals (Ref. 3).

9.4.2 Further development of many of the systems described in 9.3 are in hand. Of particular interest are:

i) Short range FM telemetry torquemeters for signal transmission from rotating to stationary plane (eg EEL torquemeter in W30 - ref. 3).

ii) On-board vibration analysis processing (eg Smiths HUM on W30 - ref. 3).

iii) Advanced rotor track and balance assessment facilities (eg refs. 9, 45).

iv) Application of Expert Systems technology to interpretation of vibration and track data (Ref. 9, 63).

v) Optical Fibres and Microwave Coatings for crack detection.

9.5 Rotor Health Monitoring Research Requirements

i) Continued development of ground-based Expert Systems aided equipment to speed resolution of the many possible faults that can effect vibration at shaft orders and blade passing orders.

ii) Continued development of blade tracking equipment and associated processing/display facilities to permit rotor tuning in all weather conditions with minimum of special flights.

iii) Development of certificatable on-board learning systems to aid discrimination between defects, trim requirements, ice accretion, and minor damage (long term).

iv) Continued development of NDI aids for in service helicopters, noting the increasing use of fibre-composite materials, thermoplastics, and elastomeric bearings (eg ref. 57).

v) Continued study of defect propagation characteristics of fibre-composite blade and hub constructions to determine potential value of integral fibre strain monitors.

vi) Continued development of signal transfer means from rotating components to the structure.

9.6 Usage and Limit Exceedance Monitoring of Rotor Systems

Airworthiness can be improved by continuous monitoring of rotor torques, speed, strains, and head moments (eg W30-30, Ref 3).

10. FLIGHT CONTROL SYSTEMS

This section includes pilots controls, non-rotating control systems, electrical and hydraulic power supplies, stability augmentation systems, Active Control Systems, and Higher Harmonic Control Systems.

10.1 General

Airworthiness in flight control systems is generally controlled by redundancy or duplication of complete systems. Critical single path features tend to be control jack bodies, attachments and attachment structure, and powered control linkages, and these are covered by safe-life procedures.

Experience indicates that duplication of systems does not always provide adequate protection against failures and hence there is scope for health monitoring. However each alternative function should be exercised regularly to reduce the likelihood of failures remaining undetected by facilitating HM. Critical units within hydraulic systems such as servo-valves are by their action prone to hard-over/ control runaway failures due to mechanical disconnects or false electrical signals, also to sticking due to particulate contamination of the fluid. This plus the mechanical aspects of hydraulic and electrical power systems (including gearbox auxiliary drives) are amendable to existing health monitoring techniques. Control systems downstream of powered actuators are required to have stiffness characteristics compatible with control stability. Wear or cracking of components in the powered linkage can therefore potentially be manifest in modification of control stability resulting in changes in vibration characteristics and loads within the system, or difficulties in control of the helicopter. Higher Harmonic Control Systems should have in-built diagnostic capability, but loads in the rest of the actuation system may be higher. Multiplexing arrangements in 'fly-by-wire' systems are protected by logic dependent on sensor reliability and continuous assessment. 'Fly-by-light' systems of the future introduce requirements for optical sensor development for all parameters currently monitored by electrical transducers. Active Control systems will have the ability to limit loads imposed on the structure and dynamic components, and will also have potential for detecting faults in these as well as self protection.

10.2 Current Health Monitoring Techniques for Flight Control Systems

i) Auxiliary drive gears - see section 8.3

ii) Hydraulic Systems - fluid pressure, temperature
- contamination (ref. 26)
- servo-jam indication

iii) Electrical Systems - voltage, current, frequency vibration.

iv) Linkages and bolts - pressure/leak - Indicating Valve, Bleeding Bolts.

v) Control thrust bearings - temperature.

10.3 Health Monitoring Developments

i) Auxiliary drive gears - see section 8.4

ii) Hydraulic Systems - contamination - reversing filter (ref 52)
- optical sensors (STC)

iii) Powered control units and linkages - loads/strain (WHL)

iv) Input/output comparison.

10.4 Health Monitoring Research Requirements

i) Optical sensors for all parameters for fly-by-light helicopters.

ii) Vibration analysis for control linkage wear/fracture, and wear in hydraulic pumps.

iii) Application of Expert Systems technology.

iv) HM developments within Active Control Systems.

11. STRUCTURE

This section covers the whole of the aircraft structure including gearbox casings/struts attachments (active or passive), undercarriages. Review papers: refs. 4, 5, 36, 38.

11.1 General

The potential contribution of health monitoring systems to the airworthiness control of structures and undercarriages is limited since direct damage tolerant design could be introduced for many areas. For existing helicopters safe-life procedures are employed, although increasing use is being made of the damage tolerance approach in terms of alternate load paths in some critical areas (refs. 4, 49). This approach will be enhanced in future airframe designs employing greater use of fail-slow fibre composites (ref. 50). For future helicopters, Rules are being formulated to require the damage tolerance approach unless impractical. Health monitoring has a role to play in extending the damage detection capability of current inspection techniques and increasing the practicality of damage tolerance design e.g. in undercarriages. Both damage tolerance and safe life approaches can be enhanced by employing usage monitoring to establish the operational loads in key locations to correlate with design assumptions, in view of the potentially very damaging effects of unanticipated loads (ref. 36). Usage monitoring exercises are progressing on a number of aircraft (MOD/WHL, BAH, BHL); the principal difficulties relate to measurement of vibratory loads, tail rotor thrust, and tail plane loads (ref. 4, 58). Whilst structural analysis techniques have improved considerably in recent years, accurate predictions of vibratory stresses throughout the structure remains a problem. The comprehensive vibration monitoring and analysis facilities developed for development 'shake tests' would be impractical in an operating environment, but monitoring and onboard processing of a number of data channels relating to representative or more critical areas is feasible, and will be undertaken with Active Gearbox Interface Control (AGIC).

Attachment integrity of secondary structure (doors, tail planes etc), is a matter of airworthiness concern, but is probably best controlled by detail design and ground check procedures.

11.2 Current Health Monitoring Techniques for Structures and Undercarriages

i) Vibration analysis - Rotor order check list procedure,
Narrow band frequency spectra.

ii) Mechanical Strain recorders.

11.3 Structural Development Aids

i) Vibration - 'Shake Tests'

ii) Strain-gauges.

iii) Comprehensive on-board digital recording systems (eg Plessey MODAS).

11.4 Structure Health and Usage Monitoring Developments

i) Load Data and Operational Data recording surveys (eg Plessey/WHL/RAE).

ii) Optical fibre crack detectors. (eg NMI/WHL/BAe).

11.5 Research Requirements, Structural Health Monitoring

i) Corrosion in metal structures.

ii) Age/Stress/environment influences on the failure of fibre-composite thermo-plastic and metal matrix composite materials.

iii) Vibration - Active Gearbox Interface Control (WHL AGIC).

iv) HM of elastomeric bearings (eg Ref. 57), anti-vibration mounts and other means of vibration attenuation at gearbox/structure interface.

12. ENGINES AND FUEL SYSTEMS

12.1 General

The flight critical aspects of civil helicopter power plants are rotor and casing integrity, structural attachments, failure of the common fuel supply system, and fire suppression. Major factors relating to engine integrity are rotor disc burst and blade loss.

Main bearing integrity is also a factor but damage progression rates are lower. Integrity of oil sealing and oil pipes is also important relative to fire hazards. Engine performance degradation and the correct functioning of power/speed limiting devices are also important airworthiness issues, particularly in operations from oil rigs and heli-pads.

The principal methods of controlling the integrity of fuel systems, engine attachments, and fire suppression equipment is by redundancy and routine checks. Health, Usage and Performance Monitoring activities relating to the Engine Change Unit have six main objectives:

i) To provide close control of usage of components designed on a safe-life basis.

ii) To maintain up to date evidence that each engine is capable of producing its single engine power rating, reliably, ie Power Assurance.

iii) To quantify the use of the engine within the certified rating structure including Limit Exceedance.

iv) To permit safe extension of the rating structure for emergencies (Ref. 4).

v) To provide data to assist the analysis of wear modes and damage progression within oil wetted parts of the engine, particularly bearings.

vi) To provide shaft imbalance monitoring (eg tracking filters).

If all these objectives are fully met it is evident that engines will achieve enhanced safety as well as improvements in cost of ownership. Review Papers: 7, 54, 55, 59, 60, 64.

12.2 System Requirements

12.2.1 Operational requirements of helicopters dictate that any system should require only minimal support from Ground Equipment. It is therefore desirable to configure any monitoring system to perform all data acquisition and computation 'on-board'. Data acquisition must be in 'real-time' but rate and timing of computation can be set to meet the necessary reaction times.

12.2.2 Ideally information display should be via cockpit for pilot and maintenance crew although a ground based data retrieval equipment can be used. Information automatically displayed to the pilot should be on a "need to know" basis although the ability to "page" certain data is advantageous.

12.2.3 To meet the objectives of para 12.1 it is necessary to derive and validate appropriate algorithms and logic to perform the following computations:-

i) Low Cycle Fatigue (LCF) of all critical engine rotatives components.

ii) Creep usage of HP/LP turbine blades.

iii) High Cycle Fatigue of drive shafts (speed and torque).

iv) Cyclic fatigue of combustion casings.

v) Power Performance Index (PPI).

vi) Limit Exceedance Logic.

Items ii), iii) or iv) may not be critical in some engine designs.

Wear debris and vibration monitoring are an integral part of the objectives listed above. Both subjects are discussed in detail in the Transmission section (para 8.2), most of the comments made apply to engine component monitoring, although differences in temperatures, oil scavenging, gear tooth loadings, and other factors can be expected to produce differences in vibration and wear debris characteristics and rejection criteria. Shaft imbalance monitoring is also required at steady running, accelerations and decelerations.

12.2.4 All monitoring systems should be used during the development of the engine to assist correlation of data and test evidence. This requirement is imperative during formal Accelerated Mission Testing (AMT) and other type approval tests.

Evidence from this test work, coupled with laboratory testing, should be used to support application for an engine modification allowing the system to be used for Executive Lifing.

12.3 Current Engine Health Monitoring

Current engine health monitoring techniques are similar to those listed under Transmissions (para 8.3.1 to 8.3.3). These are supplemented by pilot observed engine rotor speed excursions which, post flight, are converted into LCF cycles using a bulletin chart.

Usage monitoring (eg refs. 54, 60, 64), and Shaft imbalance monitoring (eg ref. 55) are now well established on fixed wing aircraft. The GE CT7/T700 engine which is also fitted to helicopters is furnished with an electro-mechanical system for LCF and Creep. An effective total engine monitoring and data management system on Concorde engines is described in ref. 59, and on USAF aircraft (ref. 60).

12.4 Engine Monitoring Development Aids

i) Gas paths analysis - seal wear and tip rubs

ii) Thermography

iii) Vibration analysis, including run-down checks.

iv) Thin Layer Activation.

v) Operational data recording surveys (eg Plessey/WHL/RR).

12.5 Engine Monitoring Systems - Development

12.5.1 Current 'on-board' monitoring is being developed in four different system configurations.

i) Integrated with all other functions within a large helicopter central processing unit (CPU) (eg ref. 3.)

ii) Integrated with Transmission Torque Monitoring in inter-seat console unit (ref. 3).

iii) Integrated within a Full Authority Digital Electronic Control (FADEC) with separate processors for high integrity. (eg ref. 56).

iv) A dedicated stand alone EMS (eg refs. 54, 64).

Systems ii) and iii) can be developed as described in para 12.2 but i) is more problematic.

12.5.2 The above are committed development programmes which could be enhanced by the further development of engine vibration monitoring and QDM data processing. Both are a natural extension of helicopter transmission monitoring since the engine is an integral part of the dynamic system. Several QDM trials are in progress on turbine engines on test beds in the UK and the USA, and on an installation on an off-shore platform.

Engine vibration data can therefore highlight part of the total system vibration as well as balance and casing characteristic changes within the engine (eg ref. 55).

12.6 Engine Monitoring Research Requirements

Outstanding problem areas are:-

- Refinement of algorithms associated with material properties.

- Corrosion, internal components and casings.

- More detailed understanding of failure modes and response characteristics to assist interpretation of vibration signals.

- Improved engine performance diagnostic routines.

- Continued development of wear debris monitoring.

- Logistics of data management off the aircraft.

Many techniques associated with engine monitoring only require persistent development to achieve their objectives. To be effective this development work requires the full commitment of both operators and certifying authorities, ie the potential improved safety and cost of ownership must be accepted by all parties, not just manufacturers.

13. CONCLUSIONS

13.1 Significant advances have been made in health and usage monitoring technology recently, including:

Transmissions

Production Helicopters:-

- pulsed electric chip detectors (many applications)
- quantitative wear debris monitoring - W30 (WHL/TEDECO)
- full-flow electrified screen - CH47D (BV/TEDECO)
- advanced vibration analysis (WHL, Chadwick-Helmuth)
- borescope and guide tube provisions - W30 (WHL) (for in-situ confirmation of wear)

Development:-

- FM telemetry torquemeters -W30 (WHL/EEL)
- Torque exposure/cumulative damage data processing - W30 (WHL/Dowty/HSDE)
- On-board vibration analysis - W30 (WHL/SI)
- Portable vibration analysis equipment - W30 (WHL/SI), general (SHL)
- Monitor filter W.30 (WHL)

Rotor Systems

Production:

- Blade spar integrity detection (several)

Development:

- strain-gauged hubs and FM telemetry (WHL/EEL)
- improved blade tracking facilities (SHL & MCTH)

Engines

Production (fixed wing/helicopters):-

- shaft vibration (tracking filters) - RB 211 (RR/Vibro-Meter)
- cycle-counting (LCF & Creep) - W30 (WHL/RR/Dowty/SI/NGTE/GE/Plessey et al)
- Power assurance monitoring - W30 (WHL/Dowty/SI/RR/GE et al - ref.64)

General

Development:

- comprehensive on-board monitoring systems (W30, EH101)
- high frequency vibration data acquisition and analysis on-board (W30 and EH101)
- portable analysers for vibration, debris and oil analysis (several)
- health monitoring system comparative evaluations on development and service aircraft and component rig tests (WHL/NAML).

Research:-

- optical fibre strain sensors for blades, hubs and structures (NMI/WHL).
- application of Expert Systems to algorithm development (WHL & SHL)

13.2 All the above advances were introduced before publication of the HARP report. This reflects the commitment of helicopter and engine manufacturers, MOD, equipment manufacturers, universities and research establishments to advancing health monitoring technology in parallel with other reliability improving technology to achieve improved airworthiness.

13.3 There is no panacea as far as health monitoring of helicopter components is concerned. Particular techniques may be more suitable to particular helicopters/components, and more than one technique is often required in order to contain possible failure modes. Vibration analysis and Expert Systems technology appear to offer wide application possibilities and flexibility.

13.4 Health monitoring should be an integral part of the total maintenance strategy and systems, whether these be on-board, or ground-based. Usage Monitoring, Performance Monitoring, and Status Monitoring can also contribute to improvement of airworthiness.

13.5 In future designs of helicopters the areas that, from an airworthiness point of view, would benefit most from the use of Health Monitoring Techniques are transmissions and rotor systems. These are flight critical systems for which the Damage Tolerance approach has limited scope using current inspection techniques, but would be greatly extended by effective health monitoring for damage detection.

Engine usage and power assurance and rotor control systems are also important areas for effective monitoring systems. Rotor track and balance systems will also contribute to airworthiness.

13.6 Attention is drawn to the points raised in section 7 concerning Health Monitoring system requirements.

14. RECOMMENDATIONS

14.1 Research and Development should be particularly encouraged/continued on:-

i) Improved reliability sensors for all parameters.

ii) Vibration Analysis: extension of existing capabilities for Transmissions, Rotor Systems, Flight Controls Systems, Structure and Engines, in terms of algorithms, implementation, and correlation with condition.

iii) Wear Debris Monitoring: extension of existing capabilities for Transmissions and Engine Oil Systems and hydraulic systems in terms of improving catch efficiency, implementation, and correlation with condition.

iv) Optical Fibre Strain Detectors: Metal and Composite Rotor Blades(?), Rotor Hubs, Control Linkages, Primary load paths in Structure and Skeletal Gearbox Casings - fibres, bonding, connectors, signal processing, correlation with condition.

v) Electrical resistance strain gauging/FM telemetry transmission for metal blades and hubs.

vi) Optical sensors, data links and interfaces for 'Fly-by-Light' applications.

vii) Improved accuracy/"intelligent" blade tracking facilities.

viii) FM Telemetry Torquemeters provide a means of measuring mean torques with high accuracy and reliability. They also have a wide frequency bandwidth which could be used for diagnosing faults in shafts, gearboxes, engines, and rotor systems.

ix) At-aircraft detection of oil contamination (hydraulic fluids and lubricants) - by particulates and water.

x) Application of Expert Systems technology to

(a) development of algorithms - individual and combined HM techniques, including trending of oil system parameters.

(b) Correlation of HM system performance data.

(c) Evaluate logic in HM system management and maintenance manuals.

(d) On-board HM systems.

xi) On-board HM processor/interface/display development.

xii) Ground-based Health and Usage Monitoring Data Management Systems.

xiii) 'Smart' sensors - sensors with dedicated processing and control interfaces.

14.2 A Helicopter Health Monitoring Advisory Group should be set up to provide a stimulus for continued improvements in health and usage monitoring technology for helicopter applications. The objectives would be to:-

i) Increase awareness of problems - components and HUM systems.

ii) Increase awareness of new solutions.

iii) Influence research - funding and technical, if necessary providing a technical monitoring function or assistance to DTI, SERC, MOD, etc.

iv) Improve operator commitment through manufacturer/operator dialogue.

v) Provide additional expert comment on draft airworthiness requirements circulated for comment (on HUM issues).

The Advisory Group should comprise representatives of airframe, engine, and equipment manufacturers, operators, and MOD. The group should liaise with MOD advisory groups on NDI and Structure Integrity.

14.3 Helicopter manufacturers should be encouraged to apply the latest health monitoring technology to development/certification tests on components to:

i) improve accuracy of life determination.

ii) ensure correlation of degradation modes with those occurring in Service (especially grossly accelerated tests and 'seeded' fault tests).

iii) validate health monitoring system performance.

They should also be encouraged to apply the latest health monitoring technology to production quality assurance tests on components to reduce incidence of 'infant mortality' in service.

Monitoring systems for such tests may need to be more sensitive than those required for damage detection in service, but on the other hand would have fewer implementation constraints.

14.4 Manufacturers, Operators and Overhaul Agencies should be encouraged to co-operate in producing data banks correlating health monitoring indications with component condition on strip, in order to:

i) improve HM technology

ii) improve airworthiness through improved feed-back to design.

14.5 The way forward with health monitoring and Certification Authorities should include:-

i) Giving incentives to helicopter manufacturers by permitting significantly greater step increases in Time Between Overhaul and reduced number of sampled components where demonstrably effective health monitoring systems are fitted and used (happening on W30).

ii) Issuing airworthiness requirements in the most general terms possible, but requiring the commitment of both manufacturer and operator (eg CAA G.811 - in draft). Failure Modes and Effects Analyses should contain recommendations for suitable HM methods where appropriate.

iii) Increasing awareness of available health monitoring systems, their performance characteristics, and their applicability to existing helicopters as well as new designs.

iv) Encouraging compliance of foreign helicopter manufacturers through their airworthiness authorities and through JAC.

v) Requiring helicopter Manufacturers, Operators, and Overhaul Agencies to identify responsibility for health and usage monitoring activities within their airworthiness management structures.

....
D G ASTRIDGE
Chairman, Industry Sub-Group
CAA Helicopter Health Monitoring
Working Group

FIGURE 1 OF APPENDIX 4

HEALTH MONITORING WORKING GROUP

TERMS OF REFERENCE

INDUSTRY SUB-GROUP

A. Consider the summarised conclusions of the five Sub-Groups, in relation to items 2 and 3 of the Health Monitoring Working Group Terms of Reference and report accordingly; ie:

"2. Establish the extent to which existing technology is capable of providing the required Health Monitoring.

3. Identify the areas where existing technology does not meet the need and suggest the timescales in which the shortfall should be made good."

NB The study should clearly indicate:

- what can be done today

- which Health Monitoring methods need development

- which Health Monitoring techniques require research

B. Provide an estimate of the effectiveness, useability, availability and cost of the various techniques.

FIGURE 2 OF APPENDIX 4

CAA HMWG INDUSTRY SUB-GROUP

```
Major Components (eg Transmission)

                    Sub-Components (safety-critical - eg gears)
                          |
                          |
                 Possible Failure Modes - damage propagation rate
                          |
                          |
                       Control
                       /    \
         Health Monitoring  Other (eg NDI)
            (or aid)
               |
               |
         HM Techniques (eg Vibration Analysis)                   completed
----------------------------------------------------------------------------
         HM Methods (eg Enhanced Signal Averaging)               required
               |
               |
         Effectiveness - alert/diagnostic
               |
               |
         Implementation
          /    |    \
  Algorithms Sensors  Processor - lab/office
               |                 \ at aircraft
               |                  \ on-board:- why necessary?
               |                               /       |      \
               |                        cockpit     flight     quick
      Development Status             indication  condition  response
          /       \       \
         /         \        \
        /           \         \
   in-service   development      research
       /\       (inc.flight        /  \
      /  \         trials)        /    \
     /    \         /    \       /      \
 aircraft other  on-going required  on-going required
  (specify) \         |             /
             \        |            /
              \       |           /
   |           problems/weaknesses
   |                  |
   |           timescale & effort required
   |                   \
   |                    \
Order In-Service List  Ordered Research Topics List
                       (inc. general requirements)
```

ATTACHMENT 1 TO APPENDIX 4

DETAILED ANALYSIS CHARTS

KEY

Item: T-Transmission, R-Rotor Systems, S-Structure and Undercarriage, F-Flight Control Systems, E-Engines.

(a) Damage propagation rate from detectability: 1-within 1 flight, 3-greater than 100 hours.

(b) Primary means of airworthiness control (see 'Abbreviations' - at front of report).

HM Aid: Whether health monitoring can aid airworthiness control.

(c) Effectiveness of HM method as an Alert and as a Diagnostic aid - 1 = good 3 = poor.

(d) Urgency of development or research requirements in relation to known problems/new helicopter designs 1 - before 1987 3 - after 1990. Also estimate of effort required in funds/resources A-small, C-large.

Under the heading PROCESSOR is indicated whether the health monitoring method requires laboratory/office facilities, whether analysis can be carried out at the aircraft, or by an on-board processor. If the latter, an indication of justification is required - whether cockpit indications are necessary, whether the defect is more easily detected at flight conditions, or whether fast response is necessary (immediately at end of flight).

Overall Feasibility (e) : Predicted timescale in which HM technique could be implemented on new helicopters.

1. Already in use on production helicopters or known to be on development/certification aircraft.

2. Technique sufficiently well developed to be applied to development aircraft.

3. Technique requiring more development or experience on aircraft and unlikely to be certificated before 1990.

Factors considered were effectiveness, reliability, cost, useability, availability, implementation requirements.

MAJOR COMPONENT :– TRANSMISSION

(FOR NOTES SEE KEY)

ITEM	SAFETY-CRITICAL SUB-COMPONENT	POSSIBLE FAILURE MODE	DAMAGE PROPAGATION RATE (a)	AIRWORTHINESS CONTROL		HEALTH MONITORING TECHNIQUE	METHOD	EFFECTIVENESS (c)		ALGORITHMS/ APPLICATION						SENSORS						ANALYSIS PROCESSOR											BIBLIOGRAPHY REF	OVERALL FEASIBILITY (e)
										IN SERVICE		DEVELOPMENT		RESEARCH		IN SERVICE		DEVELOPMENT		RESEARCH				ON BOARD			IN SERVICE		DEVELOPMENT		RESEARCH			
				METHOD	HM AID?			ALERT	DIAGNOSTIC	HELICOPTERS	OTHER	ON GOING	(d) REQD.	ON GOING	(d) REQD.	HELICOPTERS	OTHER	ON GOING	(d) REQD.	ON GOING	(d) REQD.	LAB/OFFICE	AT AIRCRAFT	COCKPIT IND.	FLIGHT CONDS.	FAST RESPONSE	HELICOPTERS	OTHER	ON GOING	(d) REQD.	ON GOING	(d) REQD.		
T 1.0	ALL GEARS, BEARINGS, & TORQUE SENSITIVE COMPONENTS	FRACTURE OR SURFACE WEAR	3	USAGE MON + LEM – SL –		CONTINUOUS	TORQUE MONITORING	N/A	N/A			WHL RAN		WHL		MGB: MANY TGB: EEL		WHL EEL				✓			✓		WHL PLESSEY		DE. SI PL HSDE LI				3 51 58	1
T 1.1	GEARS (WHEELS & PINIONS)	WEB FRACTURE INITIATED FROM BORE.	1/2	SL LEM NDI	✓	VIBRATION	ACCELEROMETER ON CASING, ENHANCED SIGNAL AVERAGING	2	1	W.30		WHL		WHL		DJB ENV✓	V-M	MANY				W. 30	D	✓ D	✓	✓			SI (W.30)				3 8 11	1
T 1.2		WEB FRACTURE INITIATED FROM TOOTH	1/2	SL LEM NDI	✓	VIBRATION	AS T1.1	1	1	W.30		WHL		WHL		DJB ENV	V-M	MANY				W. 30	D	✓ D	✓	✓			SI (W.30)				8 11	1
T 1.3		TOOTH FRACTURE	2/3	SL LEM NDI	✓	VIBRATION	AS T1.1	1	1	W.30		WHL NAML SHL		WHL NAML SHL		DJB ENV	V-M	MANY				W. 30	D	✓ D	✓	✓			SI (W.30) SHL				3 8,9	1
T 1.4		TOOTH WEAR-GROSS PITTING	3	SL TBO C LEM	✓	A) VIBN	AS T1.1	1	1	W.30		WHL NAML SHL		WHL NAML SHL		DJB ENV	V-M	MANY				W. 30	D	D	✓	✓			SI (W.30) SHL				8,9	1
						B) WEAR MONITORING	MAGNETIC PLUG	2	3	MANY	ENGINES					MANY	ENGINES	TDC/MVC															7,4	1
							DEBRIS TESTER	2	2		ENGINES					N/A		N/A		N/A		II	✓					ENGINES RR	II				27	1
							ELECTRIC CHIP DETECTOR	3	3	SEVERAL	ENGINES					MANY	ENGINES	TDC						✓									7	1
							PULSED ELECTRIC CHIP DETECTOR	1	3	SEVERAL	ENGINES	TDC/ WHL				MANY	ENGINES	TDC					✓	✓									4,7	1
							QUANTITATIVE DEBRIS MONITOR	1	3	W.30		WHL/ TDC				QDM	ENGINES	TDC		TDC			✓		✓	✓	W.30	ENGINES	TDC W.30		TDC		4,28	1
							FILTER BLOCKAGE	2	3					✓		MANY																	4	1
							INDICATING SCREEN	1	2									TDC/ BV 234						✓	✓								7	1
							DE-GAUSING CHIP DETECTOR	1	3									✓							✓								7	?
							FULL FLOW SCREEN	1	2	CH47C						TDC								✓	✓								7	1
							ELECTRO-OPTICAL DEBRIS MONITOR	1	3																✓								7	
							INDUCTIVE DEBRIS MONITOR	1	3			ENGINE						SI							✓				ENGINES SI/RR				29	1
							ON-LINE ULTRASONIC	3	3					IC				TELUS		IC					✓						IC		31	3
							ON-LINE FERROGRAPH	2	3			ENGINE																ENGINES	T				7	2
							CAPACITIVE DEBRIS MONITOR																										7	
							ABRASIVITY MONITOR	2	3			FULMER		FULMER				FULMER		FULMER		✓							FULMER		FULMER		20	3
							CHEMICAL MICROSENSORS	1	3						✓						✓											✓	32	3
						C) OIL ANALYSIS	SPECTROMETRY	3	2	MANY						—	—	—	—	—	—	✓					MANY						13,4	1
							FERROGRAPHY	3	2	SEVERAL		NAML				—	—	—	—	—	—	✓					SEVERAL						14,4	1
							FILTER WASH	3	2	SEVERAL						—	—	—	—	—	—	✓					SEVERAL						4	1
							ROTARY PARTICLE DEPOSITOR & QUANTIFIER	3	2		UCS	UCS		UCS		—	—	—	—	—	—	✓						UCS	UCS		UCS		16,4	1
							X-RAY FLUORESCENCE	3	2							—	—	—	—	—	—	✓	✓		✓	✓			TDC QUAX				7	2
							SCANNING ELECTRON MICROSCOPE	3	2							—	—	—	—	—	—	✓					WHL						8	1
							CALORIMETRY	3	2							—	—	—	—	—	—	✓											7	
							QUANTIMET	3	2			UCS		UCS		—	—	—	—	—	—	✓					UCS WHL						22	1
							RADIO ACTIVE TAGGING	3	2+							—	—	—	—	—	—	✓					N/A						40,39	1
						D) INSP. AID	BORESCOPE & GUIDE TUBES	3	1/2	W.30						—	—	—	—	—	—		✓										8	1
						E) TRANS. ERROR MEASUREMENT	OPTICAL GRATING	1	1					WHL CU							✓			✓	✓	✓			✓				17	3

MAJOR COMPONENT :— TRANSMISSION

(FOR NOTES SEE KEY)

Item	Safety-Critical Sub-Component	Possible Failure Mode	Damage Propagation Rate (a)	Airworthiness Control: Method	Airworthiness Control: HM Aid?	Health Monitoring Technique	Method	Effectiveness (c): Alert	Effectiveness (c): Diagnostic	Algorithms/Application: In Service: Helicopters	Algorithms/Application: In Service: Other	Algorithms/Application: Development: On Going	Algorithms/Application: Development: Reqd (d)	Algorithms/Application: Research: On Going	Algorithms/Application: Research: Reqd (d)	Sensors: In Service: Helicopters	Sensors: In Service: Other	Sensors: Development: On Going	Sensors: Development: Reqd (d)	Sensors: Research: On Going	Sensors: Research: Reqd (d)	Analysis Processor: Lab/Office	Analysis Processor: At-Aircraft	Analysis Processor: On Board: Cockpit Ind.	Analysis Processor: On Board: Flight Conds.	Analysis Processor: On Board: Fast Response	Analysis Processor: In Service: Helicopters	Analysis Processor: In Service: Other	Analysis Processor: Development: On Going	Analysis Processor: Development: Reqd (d)	Analysis Processor: Research: On Going	Analysis Processor: Research: Reqd (d)	Bibliography Ref	Overall Feasibility (e)
T 1.5	GEARS	TOOTH WEAR - MICRO-PITTING AND SCUFFING	3	LEM NDI TBO	✓	a) VIBN	AS T1.1	2	1																								11,	1/3
						b) WEAR DEBRIS MONITORING	AS T 1.4 B)	2	3																								11	1
						c) OIL ANALYSIS	AS T 1.4 C)	3	3																								11, 14	1
						d) INSP. MD	AS T 1.4 D)	3	1																								8	1
						e) TRANS. ERROR MEASUREMENT	AS T 1.4 E)	1	1																								17	3
T 1.6		CORROSION	3	NDI		INSP. MD	AS T 1.4 D)	3	1/2																								8	1
T 2.1	QUILL SHAFTS & SPLINES	FRACTURE	1	SL LEM NDE	✓	a) VIBN	SPECTRAL ANALYSIS	2	1			WHL				W.30						✓	D	✓	✓	✓			AS T1.1				8	1
						b) TRANS. ERROR	AS T 1.4 E)	1	1																								17	3
T 2.2		FRETTING	3	TBO	✓	AS T 1.5																												1
T 3.1	BEARINGS (GEARBOX)	RETENTION FAILURE	2	SL TBO LEM	✓	VIBRATION ANALYSIS	AS T 2.1 A)	1	1																								8, 9	1
T 3.2		FAILURE AND WEAR	3	SL TBO LEM NDI	✓	a) VIBN ANALYSIS	ACCELS ON CASING HIGH FREQ. ENVELOPING	2	1			SHL NAML WHL				W.30						✓	D		✓	✓							9, 37	2
						b) TEMP MONITORING	LOCALISED THERMOCOUPLES	1	1			WHL						EM 101	✓					✓	✓	✓	W.30		WHL SI					2
						c) WEAR DEBRIS	AS T 1.4 B	1	3																								4, 7	1
						d) OIL ANALYSIS	AS T 1.4 C	3	3																								4, 7, 14	1
						e) THERMAL IMAGING	INFRA - RED CAMERA	2	1			WHL				—							D						WHL					2
T 4.1	SEALS	DAMAGE, DISPLACEMENT, WEAR	3	C TBO	✓	REMOTE OIL LEVEL MONITORING	a) ELECTRO-OPTICAL	1	3		✓						AMPCS						✓	✓										1
							b) FLOAT/REED SWITCH	1	3		✓						E-18						✓	✓									18	2
							c) CAPACITANCE	1	3			✓						SI/WHL					✓	✓										2
							d) U-S WAVEGUIDE	1	3					✓						✓			✓	✓									41	3
							e) THERMISTOR	1	3			✓											✓	✓										2
T 5.1	CASINGS & ATTACHMENTS	FRACTURE	1	SL LEM NDE C	✓	a) VIBN	ACCELS - MODAL RESPONSE	2	3					WHL		W.30						✓												3
						b) OIL LEAK	OIL PRESSURE	2	3	✓						✓								✓										3
							OIL LEVEL (AS T.4.1)	2	3	✓	✓					C	✓	✓					✓	✓										3
T 5.2		CORROSION	3	NDE C		HYDROGEN DETECTORS		2	2									CORRON															19	3
T 6.1	OIL SYSTEMS	FRACTURE/ LEAKAGE	1	SL C NDE WEAR MON.	✓	OIL LEAK	a) OIL PRESS as T.5.1	1	2							✓																		1
							b) OIL LEVEL as T.5.1	2	3							✓																		1
T 6.2		JET BLOCKAGE	1/2	C FILTER. WEAR MON	✓	a) OIL PRESS.	ACCURATE/DISTRIBUTED	3	3										✓					✓										3
						b) OIL FLOW.	" "	3	3										✓					✓										3
						c) VIS. AIDS.	BORESCOPE	3	1							W.30						✓												1
T 6.3		PUMP FAILURE	1	SL TBO WEAR MON.	✓	OIL PRESS	COCKPIT INST.	1	2							✓								✓										1
						OIL TEMP	COCKPIT INST.	1	2							✓								✓										1
T 6.4		COOLER BLOCKAGE	1/2	C FILTER WEAR MON.	✓	OIL PRESS OIL TEMP	} AS T. 6.3.	1	2																									1
T 6.5		CONTAMINATION - PARTICULATES	3	C	✓	a) FILTER BLOCKAGE	POP-OUT INDICATOR/ OIL PRESSURE	1	2							✓						✓		✓										1, 1
						b) COMPARATOR PATCH TEST.		3	1								TC		✓		✓												26	2
						c) REVERSING FILTER		3	1									BATH.U				✓							BATH.U				52	2
		- WATER	3	C	✓			3	1											IC	✓	✓									IC		25	1
		FLUIDS	3	C	✓			3	1												✓													1

MAJOR COMPONENT :— TRANSMISSION (FOR NOTES SEE KEY) PAGE. T3.

ITEM	SAFETY-CRITICAL SUB-COMPONENT	POSSIBLE FAILURE MODE	DAMAGE PROPAGATION RATE (a)	AIRWORTHINESS CONTROL: METHOD	AIRWORTHINESS CONTROL: HM AID?	HEALTH MONITORING TECHNIQUE	METHOD	EFFECTIVENESS (c): ALERT	EFFECTIVENESS (c): DIAGNOSTIC	ALGORITHMS/APPLICATION: IN SERVICE: HELICOPTERS	ALGORITHMS/APPLICATION: IN SERVICE: OTHER	ALGORITHMS/APPLICATION: DEVELOPMENT: ON GOING	ALGORITHMS/APPLICATION: DEVELOPMENT: (d) REQD.	ALGORITHMS/APPLICATION: RESEARCH: ON GOING	ALGORITHMS/APPLICATION: RESEARCH: (d) REQD.	SENSORS: IN SERVICE: HELICOPTERS	SENSORS: IN SERVICE: OTHER	SENSORS: DEVELOPMENT: ON GOING	SENSORS: DEVELOPMENT: (d) REQD.	SENSORS: RESEARCH: ON GOING	SENSORS: RESEARCH: (d) REQD.	ANALYSIS PROCESSOR: LAB/OFFICE	ANALYSIS PROCESSOR: AT-AIRCRAFT	ANALYSIS PROCESSOR: ON BOARD: COCKPIT IND.	ANALYSIS PROCESSOR: ON BOARD: FLIGHT CONDS.	ANALYSIS PROCESSOR: ON BOARD: FAST RESPONSE	ANALYSIS PROCESSOR: IN SERVICE: HELICOPTERS	ANALYSIS PROCESSOR: IN SERVICE: OTHER	ANALYSIS PROCESSOR: DEVELOPMENT: ON GOING	ANALYSIS PROCESSOR: DEVELOPMENT: (d) REQD.	ANALYSIS PROCESSOR: RESEARCH: ON GOING	ANALYSIS PROCESSOR: RESEARCH: (d) REQD.	BIBLIOGRAPHY REF	OVERALL FEASIBILITY (e)
T 7.1.	COUPLINGS	WEAR/FRACTURE	3	SL TBO C LEM	✓	VIBN.	SPECTRAL ANALYSIS	1	1	W.30		WHL				W.30						W 30							SI				8	1
T 8.1	CLUTCH	WEAR/FRACTURE	3	SL TBO C LEM																														
T 9.1.	TAIL DRIVE SHAFT BRGS.	WEAR/FRACTURE/SEIZURE	3	SL TBO C LEM	✓	a) TEMP.R	THERMOCOUPLES	1	1								✓						✓		✓	✓			SI					1
						b) VIBRATION	SPECTRA / HFE	1	1							W.30						✓	✓						SI				37	1
						c) SHOCK	SHOCK PULSE METER	1	1			US ARMY					SPM	✓					✓					SPM	✓		✓		62	1
T 10.1	ROTOR BRAKE	WEAR	3	C																														1
		INADVERTENT ENGAGEMENT — FIRE	1	SL TBO	✓	a) TEMPERATURE	THERMOCOUPLES	1	1																									1
						b) DISPLACEMENT	LVDT	1	1																									1

MAJOR COMPONENT :— ROTOR SYSTEMS (FOR NOTES SEE KEY) PAGE. R1

ITEM	SAFETY-CRITICAL SUB-COMPONENT	POSSIBLE FAILURE MODE	(a) DAMAGE PROPAGATION RATE	AIRWORTHINESS CONTROL: METHOD	AIRWORTHINESS CONTROL: HM AID?	HEALTH MONITORING TECHNIQUE	METHOD	EFFECTIVENESS (c): ALERT	EFFECTIVENESS (c): DIAGNOSTIC	ALGORITHMS/APPLICATION: IN SERVICE: HELICOPTERS	ALGORITHMS/APPLICATION: IN SERVICE: OTHER	ALGORITHMS/APPLICATION: DEVELOPMENT: ON GOING	ALGORITHMS/APPLICATION: DEVELOPMENT: (d) REQD?	ALGORITHMS/APPLICATION: RESEARCH: ON GOING	ALGORITHMS/APPLICATION: RESEARCH: (d) REQD.	SENSORS: IN SERVICE: HELICOPTERS	SENSORS: IN SERVICE: OTHER	SENSORS: DEVELOPMENT: ON GOING	SENSORS: DEVELOPMENT: (d) REQD.	SENSORS: RESEARCH: ON GOING	SENSORS: RESEARCH: (d) REQD?	ANALYSIS PROCESSOR: LAB/OFFICE	ANALYSIS PROCESSOR: AT-AIRCRAFT	ANALYSIS PROCESSOR: ON BOARD: COCKPIT IND.	ANALYSIS PROCESSOR: ON BOARD: FLIGHT CONDS.	ANALYSIS PROCESSOR: ON BOARD: FAST RESPONSE	ANALYSIS PROCESSOR: IN SERVICE: HELICOPTERS	ANALYSIS PROCESSOR: IN SERVICE: OTHER	ANALYSIS PROCESSOR: DEVELOPMENT: ON GOING	ANALYSIS PROCESSOR: DEVELOPMENT: (d) REQD.	ANALYSIS PROCESSOR: RESEARCH: ON GOING	ANALYSIS PROCESSOR: RESEARCH: (d) REQD.	BIBLIOGRAPHY REF	(e) OVERALL FEASIBILITY
R 1.0	HUBS, BLADES, ATTACHMENTS BEARINGS DAMPERS	LOAD AND TIME DEPENDENT FAILURES	3	USAGE inc. MPFL TAXI			CONTINUOUS MON OF ROTOR STOP-STARTS, TQL'S, FLYING HOURS, STRAINS, TORQUES, ETC.	N/A	N/A			WHL		WHL RAE		✓		WHL et al				✓			✓		WHL PLESSEY RSC		SMITHS PLESSEY et al				3 51 58	1
R 1.1	BLADE	DETACHMENT -ATTACHMENT FRACTURE	1	C DT NDI LEM SL	✓	A) VIBN (IR) (i) Self S (ii) VCL	ACCEL ON HEAD WITH SRFMT, OR ACCEL ON STRUCTURE	2	2	(ii) WHL				(i) SHL?	(i) ✓	MANY								✓	✓	✓			✓				4 9 38	1/3
						STRAIN	B) STRAIN-GAUGE + SRFMT	2	1			WHL		RAE		WHL EEL		WHL EEL						✓	✓	✓			✓				51 58	1/3
							C) OPTICAL FIBRE BONDED TO METAL EMBEDDED IN COMPOSITE	2	1			WHL						STC NMI		Sh. U Sh. U				✓	✓	✓			✓		WHL BAe NMI		4	3
							D) METAL WIRE / FOIL	2	1			WHL												✓	✓	✓			✓					3
							E) CONDUCTING PAINT	3	2	BELL		WHL												✓	✓	✓			✓					3
							F) MICROWAVE COATING	2	1					Batelle						Batelle				✓	✓	✓			✓					3
						G) BLADE TRACKING	ADVANCED TRACKER & PROCESSING	2	1			SHL MCTH		SHL MOD WHL				SHL MCTH						✓	✓	✓			✓				9 38	2/3
						H) HF NOISE	ACOUSTIC EMISSION	2	1					C4 CIT HARWELL	✓			BAe CIT HARWELL						✓	✓	✓			✓				23	3
		I) CORROSION INITIATED	3	DESIGN + NDI	X																												19	
R 1.2		J) ATTACHMENT BOLT FRACTURE	1	DT SL NDI LEM BB	X																													
R 1.3		K) SPAR FRACTURE	1	SL DT NDI LEM C	✓	PRESSURE LOSS (METAL BLADE)	(i) ON BLADE	2	2	MANY						IBIS							✓				GAUGE							1
							(ii) REMOTE	1/2	2	✓						BIM ISIS			✓					✓	✓	✓	GAUGE							1
						VIBN. AS A)	STRAIN AS B)-F)	TRACKING AS G)			AE	AS H)																	✓					AS ABOVE
R 1.4		L) DISBOND/ DELAMINATION IMPACT DAMAGE	2	C DT NDI LEM	✓	VIBN. AS A)	TRACKING AS G)	1/2	2														✓		✓				✓					2/3
R 1.5		M) LOSS OF TIP CAP, L/E, T/E, BAL. WEIGHTS.	2	C LEM Sacf FOR L/E	✓	VIBN. AS A)	TRACKING G) BALANCE M)	1	2	✓						✓							✓ ✓	✓	✓	✓			✓					1
R 1.6		N) WATER INGRESS/UPTAKE	3	NDI	✓	VIBN. AS A) BALANCE M)	TRACKING AS G)	2	3	✓						✓							✓						✓					1
R 1.7		O) CORROSION	3	C NDI DESIGN	X																													
R 1.8		P) ICING	1	DEICING + ICE ACCRETION MONITORING	X			1	1	✓						LEIGH																		

MAJOR COMPONENT :- ROTOR SYSTEMS (FOR NOTES SEE KEY) PAGE. R2

ITEM	SAFETY-CRITICAL SUB-COMPONENT	POSSIBLE FAILURE MODE	DAMAGE PROPAGATION RATE (a)	AIRWORTHINESS CONTROL: METHOD	AIRWORTHINESS CONTROL: HM AID?	HEALTH MONITORING TECHNIQUE	METHOD	EFFECTIVENESS (c): ALERT	EFFECTIVENESS (c): DIAGNOSTIC	ALGORITHMS/APPLICATION: IN SERVICE HELICOPTERS	ALGORITHMS/APPLICATION: IN SERVICE OTHER	ALGORITHMS/APPLICATION: DEVELOPMENT ON GOING	ALGORITHMS/APPLICATION: DEVELOPMENT (d) REQD.	ALGORITHMS/APPLICATION: RESEARCH ON GOING	ALGORITHMS/APPLICATION: RESEARCH (d) REQD.	SENSORS: IN SERVICE HELICOPTERS	SENSORS: IN SERVICE OTHER	SENSORS: DEVELOPMENT ON GOING	SENSORS: DEVELOPMENT (d) REQD.	SENSORS: RESEARCH ON GOING	SENSORS: RESEARCH (d) REQD.	ANALYSIS PROCESSOR: LAB/OFFICE	ANALYSIS PROCESSOR: AT-AIRCRAFT	ANALYSIS PROCESSOR: ON BOARD COCKPIT IND.	ANALYSIS PROCESSOR: ON BOARD FLIGHT CONDS.	ANALYSIS PROCESSOR: ON BOARD FAST RESPONSE	ANALYSIS PROCESSOR: IN SERVICE HELICOPTERS	ANALYSIS PROCESSOR: IN SERVICE OTHER	ANALYSIS PROCESSOR: DEVELOPMENT ON GOING	ANALYSIS PROCESSOR: DEVELOPMENT (d) REQD.	ANALYSIS PROCESSOR: RESEARCH ON GOING	ANALYSIS PROCESSOR: RESEARCH (d) REQD.	BIBLIOGRAPHY REF	OVERALL FEASIBILITY (e)
R 2.1	HUB	BLADE ATTACHMENT FRACTURE AS R1.1						2	2																				✓					2/3
R 2.2		HUB FRACTURE	1	DT SL NDI LEM	✓	VIBN AS A), TRACKING AS G)		1	2															✓	✓	✓			✓					2/3
R 2.3		ATTACHMENT BOLTS LOOSE/ BROKN, SPLINE WEAR	2	C DT NDI LEM	✓	VIBN AS A), TRACKING AS G)		1	2														✓	✓	✓	✓			✓					2
R 2.4		BEARING WEAR OR FAILURE (R/E, PLAIN)	3	C DT NDI LEM	✓	VIBN AS A),		2	2														✓										44	2
						TRACKING G)		1	1																									
						WEAR DEBRIS AS T1.4 B)		2	1														✓											2
						TEMPERATURE	RESISTANCE PROBE	1	1	WHL		WHL				MANY								✓			GAUGE						4	1
						FRICTION	CONTROL LOAD	2	3				✓			✓							✓		✓				✓				4	2
						H.F. NOISE	ACOUSTIC EMISSION	2	2					CU CIT						CU CIT			✓						✓				23	3
R 2.5		ELASTOMERIC BRG. WEAR	3	C LEM	✓	VIBN AS A)	TRACKING AS G)	1	1																									
						TEMPERATURE	THERMOGRAPHY	2	1																								57	2
R 3.1	MAST/SHAFT	FRACTURE	1	C DT NDI LEM	✓	VIBN AS A)		1	2															✓	✓	✓								2/3
R 4.1	DAMPERS	ATTACHMENT LOOSE/FAIL	1	C NDI LEM	✓	VIBN AS A)	TRACKING AS G)	1	1					WHL SHL		✓							✓		✓				✓					2
R 4.2		LEAK/FAIL	2	C	✓	VIBN AS A)	TRACKING AS G)	2	1					WHL SHL		✓							✓		✓									1
R 5.1	VIBRATION ABSORBERS	RESONANCE	1		✓	VIBRATION	'BONK-METER'	1	1	WHL						WHL							✓				WHL							1
R 6.1	ROTATING CONTROLS	TRACK ROD BEARING WEAR	3	C	✓	VIBN	IR, HR LEVELS VCL	1	1	MOST		WHL				MOST							✓				MOST						4	1

MAJOR COMPONENT :- FLIGHT CONTROL SYSTEMS. (FOR NOTES SEE KEY)

ITEM	SAFETY-CRITICAL SUB-COMPONENT	POSSIBLE FAILURE MODE	DAMAGE PROPAGATION RATE (a)	AIRWORTHINESS CONTROL METHOD	AIRWORTHINESS CONTROL HM AID?	HEALTH MONITORING TECHNIQUE	METHOD	EFFECTIVENESS (c) ALERT	EFFECTIVENESS (c) DIAGNOSTIC	ALGORITHMS/APPLICATION IN SERVICE HELICOPTERS	ALGORITHMS/APPLICATION IN SERVICE OTHER	ALGORITHMS/APPLICATION DEVELOPMENT ON GOING	ALGORITHMS/APPLICATION DEVELOPMENT (d) REQD.	ALGORITHMS/APPLICATION RESEARCH ON GOING	ALGORITHMS/APPLICATION RESEARCH (d) REQD.	SENSORS IN SERVICE HELICOPTERS	SENSORS IN SERVICE OTHER	SENSORS DEVELOPMENT ON GOING	SENSORS DEVELOPMENT (d) REQD.	SENSORS RESEARCH ON GOING	SENSORS RESEARCH (d) REQD.	ANALYSIS PROCESSOR LAB/OFFICE	ANALYSIS PROCESSOR AT-AIRCRAFT	ANALYSIS PROCESSOR ON BOARD COCKPIT IND.	ANALYSIS PROCESSOR ON BOARD FLIGHT CONDS.	ANALYSIS PROCESSOR ON BOARD FAST RESPONSE	ANALYSIS PROCESSOR IN SERVICE HELICOPTERS	ANALYSIS PROCESSOR IN SERVICE OTHER	ANALYSIS PROCESSOR DEVELOPMENT ON GOING	ANALYSIS PROCESSOR DEVELOPMENT (d) REQD.	ANALYSIS PROCESSOR RESEARCH ON GOING	ANALYSIS PROCESSOR RESEARCH (d) REQD.	BIBLIOGRAPHY REF	OVERALL FEASIBILITY (e)
F1	ALL POWERED CONTROLS	FRACTURE		USAGE MON.			AS S1.0 + STRAIN MON.	AS		S1.0																							3, 51, 58	3
F2.1	ACTUATORS/ LINKAGES	FRACTURE	1/3	SL DT LI LEM C MPL	✓	a) VIBN	i) RESPONSE	AS		S 2(a)(i)																								2
							ii) VCL	AS		S 2(a)(ii)																								1
						b) LOAD	STRAIN GAUGE	AS		R 1.1(b)																								1
						c) CRACK MON.	i) CRACK WIRE	AS		R 1.1(a)																								1
							ii) OPTICAL FIBRE	AS		R 1.1(c)																								2
F2.2	HOLLOW LINKS	"	1/3	C NDI	✓	PRESSURE/LEAK	i) SCHRAEDER VALVE	1	1	NHL						NHL							✓		✓									2
							ii) DYE PENETRANT	2	2		BAe	BB					BB	BB					✓		✓									1
F2.3		BRG WEAR/ SPLINE WEAR	3	C	✓	a) VIBN	AS F2.1.(a)	2	2																									1
						b) LOAD	AS F2.1(b)	1	1																									2
F3.1	FLIGHT CONTROL PROCESSORS/ INPUTS	AFCS ACT MALFUNCTION	1	Dup	✓	BITE																												1
F3.2		CONTROL INPUT FRACTURE/WEAR	3	C																														1
F4	OPTICAL FCS				✓	BITE	FIBRE OPTIC SENSORS	1	1					✓	✓			✓	✓	✓	✓													
F5.1	HYDRAULIC SYSTEMS	PUMP FAILURE	1	Dup	✓	a) PRESSURE	HF TRENDS	1	1																				✓	✓	✓	✓		3
						b) VIBN	ESA		AS	T1.1																								1
						c) CONTAMN.	i) FILTER BLOCKAGE	3	3	✓						✓		✓		✓			✓										8	1
							ii) REVERSING FILTER	3	3									✓		✓														1
							iii) PATCH TEST	3	2	✓													BU										52	2
F5.2		PIPE FRACTURE/ LEAKAGE	1	SL, C	✓	a) PRESS	INDICATOR	1	2	✓						✓	✓	TC		TC			TC										26	1
						b) FLUID LEVEL	AS T4.1	2	2	✓						✓								✓										1
F5.3		SERVO-JAMS	1	Dup C	✓	POSITION	LVDT		AS	S3						✓	✓	✓					✓	✓										1
F5.4		CONTAMINATION	1	C	✓	AS F5.1 (c).																												1
F5.5		RESERVOIR LEAKAGE	1	SL C	✓	AS F5.2																												1
F6.1	ELECTRICAL POWER SYS.	GENERATOR FAILURE	1	Dup C	✓	a) SYSTEM	INDICATORS (V,I)	1	2																									1
						b) VIBN	SHAFT ORDERS + HFE		AS	T 3.2(a)																								1
						c) TEMPS	THERMOCOUPLES		AS	T 3.2(b)																								1
						d) STRAY	FLUX	1	1																									1
F7	AUX. DRIVE GEARS/SHAFTS	FRACTURE/ WEAR		AS TRANSMISSION SECTION																													53	1
F8	COCKPIT INSTS & DISPLAYS	FAILURE OF INST. OR LIGHTING	1	Dup	✓	BITE																												1
F9	NAV AIDS	FAILURE/MALF.	1	Dup	✓	BITE																												1
F10	HUM SYSTEMS	FAILURE/ MALFUNCTION	1	Dup	✓	BITE																												1

MAJOR COMPONENT :- STRUCTURE & UNDERCARRIAGES (FOR NOTES SEE KEY)

ITEM	SAFETY-CRITICAL SUB-COMPONENT	POSSIBLE FAILURE MODE	(a) DAMAGE PROPAGATION RATE	AIRWORTHINESS CONTROL: METHOD	AIRWORTHINESS CONTROL: HM AID?	HEALTH MONITORING TECHNIQUE	METHOD	EFFECTIVENESS (c): ALERT	EFFECTIVENESS (c): DIAGNOSTIC	ALGORITHMS/APPLICATION: IN SERVICE: HELICOPTERS	ALGORITHMS/APPLICATION: IN SERVICE: OTHER	ALGORITHMS/APPLICATION: DEVELOPMENT: ON GOING	ALGORITHMS/APPLICATION: DEVELOPMENT: (d) REQD.	ALGORITHMS/APPLICATION: RESEARCH: ON GOING	ALGORITHMS/APPLICATION: RESEARCH: (d) REQD.	SENSORS: IN SERVICE: HELICOPTERS	SENSORS: IN SERVICE: OTHER	SENSORS: DEVELOPMENT: ON GOING	SENSORS: DEVELOPMENT: (d) REQD.	SENSORS: RESEARCH: ON GOING	SENSORS: RESEARCH: (d) REQD.	ANALYSIS PROCESSOR: LAB/OFFICE	ANALYSIS PROCESSOR: AT-AIRCRAFT	ANALYSIS PROCESSOR: ON BOARD: COCKPIT IND.	ANALYSIS PROCESSOR: ON BOARD: FLIGHT CONDS.	ANALYSIS PROCESSOR: ON BOARD: FAST RESPONSE	ANALYSIS PROCESSOR: IN SERVICE: HELICOPTERS	ANALYSIS PROCESSOR: IN SERVICE: OTHER	ANALYSIS PROCESSOR: DEVELOPMENT: ON GOING	ANALYSIS PROCESSOR: DEVELOPMENT: (d) REQD.	ANALYSIS PROCESSOR: RESEARCH: ON GOING	ANALYSIS PROCESSOR: RESEARCH: (d) REQD.	BIBLIOGRAPHY REF	(e) OVERALL FEASIBILITY
S 1.0	ALL COMPONENTS	FRACTURE/ WEAR		USAGE MON.			MANOEUVRES, CG, AUW, CONTROL INPUTS/RESPONSE VIBRATORY LOADS AERODYNAMIC LOADS EXTL LOADS.	3	3			WHL BW BHL MoD RAE	✓			✓						✓			✓		PLESSEY REC						3 51 58	3
S 2	ATTACHMENT STRUCTURE -GEARBOXES	FRACTURE/ WEAR	2	SL C NDI DT U LEM MPFL	✓	(a) VIBN	(i) RESPONSE	1	2													✓		✓	✓	✓			SI				4 38	2
							(ii) VCL	2	2	✓			✓		✓	DTS ENDY							✓		✓	✓			PLESSEY RSC					2
						(b) CRACK MON	(i) CRACK WIRE	AS R 1.1 (d)																										2
							(ii) OPTICAL FIBRE	AS R 1.1 (c)																										2
							(iii) STRAIN-GAUGE	AS R 1.1 (b)																										1
							(iv) MECH. STRAIN REC	3	2	✓	FWA					LEIGH	LEIGH					✓			✓		✓	BAe						1
S 3	ANTI-VIBN MOUNTS	FAILURE/ WEAR	2	DITTO	✓	(a) VIBN	AS S2(a)	1	2																									2
						(b) DEFLN	LVDT	2	1				✓				✓							✓	✓	✓			SI					1
						(c) TEMPS (ELASTOMERICS)		AS R 2.5							✓																			2
S4.1	AGIC SYSTEM	PROCESSOR	1	DUP	✓	BITE		1	1																									3 AGIC
S4.2		JACKS/LINES LINKAGES	2	SL C U LEM	✓	(a) VIBN	AS S2(a)	1	2																									
						(b) LOAD.	STRAIN-GAUGE	AS R1.1(b)																										
S 5.	MAIN LOAD PATHS	FRACTURE	2	AS S.2	✓	(a) VIBN	AS S2(a)	2	3																									2
						(b) CRACK MON	AS S2(b)	2	2																									2
S6.1	AIRFRAME	FRACTURE	3	AS S.2	✓	AS S.2		2	3																									3
S6.2		DAMAGE	1/3	C	✓	VIBN.	AS S.2(a)	2	3																									2
S6.3		CORROSION	3	C NDI																														
S 7	SECONDARY STRUCTURE	DETACHMENT	1	C [illegible] DESIGN.																														
S 8	UNDERCARRIAGE	FRACTURE	1	AS S.2	✓	CRACK MON	AS S.2(b)	2	1																									
S9.1	UNDER-SLUNG LOADS	HOOK FRACTURE	1	AS S.2	✓	CRACK MON	AS S2(b)	2	1																									2
S9.2		CABLES/ATTACH	1	AS S2	✓	CRACK MON	AS S2(b)	2	1																									2
S10.1	PILOT'S SEAT ETC	FRACTURE	1/3	SL C	✓	CRACK MON	AS S2(b)	2	1																									2
S10.2		FIRE	1	FLAME DETECTORS / FIRE SUPPRESSION																														2

MAJOR COMPONENT :– ENGINES & FUEL SYSTEMS. (FOR NOTES SEE KEY)

ITEM	SAFETY-CRITICAL SUB-COMPONENT	POSSIBLE FAILURE MODE	DAMAGE PROPAGATION RATE (a)	AIRWORTHINESS CONTROL: METHOD	AIRWORTHINESS CONTROL: HM AID?	HEALTH MONITORING TECHNIQUE	METHOD	EFFECTIVENESS (c): ALERT	EFFECTIVENESS (c): DIAGNOSTIC	ALGORITHMS/APPLICATION: IN SERVICE – HELICOPTERS	IN SERVICE – OTHER	DEVELOPMENT – ON GOING	DEVELOPMENT – REQD. (d)	RESEARCH – ON GOING	RESEARCH – REQD. (d)	SENSORS: IN SERVICE – HELICOPTERS	IN SERVICE – OTHER	DEVELOPMENT – ON GOING	DEVELOPMENT – REQD. (d)	RESEARCH – ON GOING	RESEARCH – REQD. (d)	ANALYSIS PROCESSOR: LAB/OFFICE	AT-AIRCRAFT	ON BOARD – COCKPIT IND.	ON BOARD – FLIGHT CONDS.	ON BOARD – FAST RESPONSE	IN SERVICE – HELICOPTERS	IN SERVICE – OTHER	DEVELOPMENT – ON GOING	DEVELOPMENT – REQD. (d)	RESEARCH – ON GOING	RESEARCH – REQD. (d)	BIBLIOGRAPHY REF	OVERALL FEASIBILITY (e)
E 1.1	ROTATIVES	a) DISK/HUB FRACTURE → BURST	1	SL-CYCLES	✓	a) LCF, CREEP LEM	i) MANUAL LOGGING	3	3	MOST	FWA																							1
							ii) COMPUTER	2	2	CT7	FWA	MANY		NGTE		MOST		✓					✓		✓		CT7		MANY				64	1
						b) VIBN.	i) TRACKING FILTERS	1	1		FWA	V-M		SHL		✓	MANY	MANY					✓	✓	✓	✓		RB 211 et al.	V-M				55	1
							ii) BROAD BAND LEVELS	3	3	CT7	FWA					✓	"	"				✓		✓	✓	✓		✓	BA				59	3
							iii) NARROW BAND LEVELS	2	2	SOME						"	"	"						✓	✓	✓			V-M				55	2
E 1.2		BLADE FRACTURE	1	SL-CYCLES PM C	✓	a) VIBN.	AS 1.1(b)	1/3	1/3				1B		2B	✓								✓	✓	✓								1/3
						b) PERFORMCE (PPI)	i) MANUAL LOGGING	2	2	ALL	FWA					✓	✓					✓							BA				59	1/3
							ii) COMPUTER	1	2	SOME	FWA	✓			1A	SOME	✓	✓	✓					✓	✓	✓	SOME	FWA	✓	✓			64	1
						c) VISUAL	BORESCOPE	3	1		FWA	✓											✓											1
E 2.	PRESSURE CASINGS	a) CRACK	3	SL-CYCLES	✓	a) PRESSURE CYCLES	i) MANUAL	2	3													✓												3
		b) BURST	1				ii) COMPUTER	2	3				1A					✓						✓	✓	✓				✓				1
						b GAS PATH ANALYSIS.		2	1						2B		FWA						✓											3
E 3	BEARINGS	AS T.3.1 AND T.3.2.																																1
E 4	GEARS	AS T1.0 → T.1.5																																
E 5.1	BEARING SUPPORT CASINGS.	CRACK/DISTORTION	1/2	SL-CYCLES C	✓	VIBN. – AS E 1.1(b)																												1
					PM	PERFORMANCE – AS E 1.2(b)																												1
						VISUAL – AS E 1.2(c)																												1
E 5.2		EROSION	3	SL-CYCLES (CREEP)	PM	PERFORMANCE – AS E 1.2(b)																												1
					C	VISUAL – AS E 1.2.(c)																												1
E 6.1	NOZZLES	CRACK/DISTORTION	1/3	SL-CYCLES (CREEP)	PM	PERFORMANCE – AS E.1.2(b)																												1
					C	VISUAL – AS E1.2 (c)																												1
E 6.2		EROSION	3	AS		E.5.2.																												1
E 7	COMBUSTION CAN.	CRACK/EROSION	1/3	SL-CYCLES (CREEP)		AS E 6.1 & 6.2																												1
E 8	OIL SYSTEM	AS T. 6.1 → T 6.5																																1
E 9	FUEL CONTROL SYSTEM (DIGITAL)	INSTABILITIES	1	DUP C		BITE		1	2			✓				✓								✓	✓	✓	✓			1A				1
E 10	SENSORS	(FCU MALFN, COCKPIT INSTN)	1	DUP. C		DATA COMPARISON/VALIDATION		1	1			✓												✓	✓	✓				1A				1
E 11	ACCESSORIES	MALFUNCN	2	SL C		FUNCTION CHECKS		2	2				1A										✓	✓	✓	✓				1A				1
E 12	MIN POWER REQTS	COMBN OF E1, 6, 7, 10	2	C	PM	PPI – AS E1.2(b)																												1
E 13.1	ATTACHMENT TO A/C & G-BOX	FRACTURE	1	BT, C	✓	VIBN	AS E 1.1(b)	2	3				1A			✓								✓	✓	✓			✓					2
13.2		BEARING WEAR	3	C	✓	VIBN	AS E 1.1(b)	1	2	W.30			1A			✓						✓	✓	✓	✓				✓					1
E 14.1	FUEL SYSTEM.	FUEL GAUGE	1	DUP		PPI as E 1.2(b)																												
14.2		TANK/PIPE RUPTURE	1	CI, C																														
14.3		VALVE STICK	1	DUP, C																														
14.4		FUEL CONTAMN	1	PERF																														
14.5		LP PUMP FAILURE	1	CI																														
E 15	FIRE SUPPRESSION	SYSTEM FAILURE		DUP C																														

CIVIL AVIATION AUTHORITY

SECTION G
ROTORCRAFT

BRITISH CIVIL AIRWORTHINESS REQUIREMENTS
PAPER NO. G811
2ND DRAFT OF ISSUE 1
31st December 1984

HEALTH MONITORING

INTRODUCTION

This proposal stems from an overall review of the Rotor Transmission requirements, and the conclusions of the AWD Committee which reviewed helicopter safety.

It is recognised that the desired level of safety proposed by Paper G778 is unlikely to be provided by the Rotor/Transmission system using current methods, and that to do so will require the exploitation of damage tolerance characteristics using health monitoring to detect deterioration before failure occurs.

Health Monitoring is currently available in some forms for the Rotor/Transmission system, for example, oil analysis, chip detectors, vibration and noise analysis and use of pressurised components. However, it is apparent that less than full use is being made of such methods and requirements appear necessary so that manufacturers design for and develop monitoring methods, and provide the necessary facilities, including tappings and instrumentation.

Arising from this, there is a need to clarify the criteria of acceptability for health monitoring in order that operators may develop the necessary skills and make a management commitment to the principles involved when operating equipment of this kind.

The proposals in this Paper are intended

(a) to explain how the safety of a rotor and transmission system should be substantiated by the constructor when health monitoring techniques are to be employed in service.

(b) to state the additional requirements to be satisfied by operators/maintenance organisations responsible for helicopters which depend on health monitoring techniques for their continuing airworthiness.

DISCUSSION

The completion of a Safety Assessment as proposed in Paper G778 may identify a number of critical failure modes in the Rotor/Transmission system.

Current mechanical systems with the complexity of a typical helicopter transmission are unlikely to satisfy the reliability criteria for integrity associated with Group A operations proposed in Paper G778, if reliance continues to be placed only on certification testing, and the safe lives established at that time, and the traditional life development in service. The latter is of decreasing benefit as the time between overhauls is increased. If higher levels of reliability are to be achieved, recognition has to be given to the fact that many failure mechanisms are not strictly age related, therefore effective health monitoring techniques must be applied throughout the life of the component.

Damage tolerance as an acceptable approach for preventing structural failures can also be directly relevant to many dynamic components in the Rotor system. Some damage tolerance concepts are equally relevant to the internals of gearboxes, but will depend on the availability of suitable inspection techniques.

Although it is envisaged that acceptance of the Safety Assessment will give some impetus to health monitoring, the proposed requirements are judged to be necessary because neither the need for such monitoring, nor the benefits which can be claimed can be quantified as would be necessary under the Safety Assessment.

These proposals call for the application of health monitoring to gearboxes, and other Rotor system components.

In order to implement Health Monitoring procedures, changes are needed to BCAR Section 'A' and suggestions are made in this Paper as to how this could be done by adding a supplement to Chapter A6-4. If the principle is agreed then proposals will be made for amendment to Section A by the usual procedures.

RELATIONSHIP TO FAR's

There are no equivalent FAR's, but there is an NPRM in the pipeline requiring chip detectors in transmission gearboxes.

PROPOSALS

Material differences between the proposals of this Paper and the current requirements of Section G are indicated with marginal lines.

CHAPTER G4-9*

Add the following new paragraph as 2.5, and renumber subsequent paragraphs accordingly:-

"2.5 The design of the Rotor and Transmission System shall be such that where health monitoring techniques are applied to critical components, including internal parts of gearboxes, they shall be practicable and effective.

2.5.1 An effective health monitoring technique shall be established and shall form part of the Safety Assessment conducted in accordance with paragraph 4, particularly in cases where failure cannot be reliably controlled by normal lifing techniques because of the random nature of the failure, such as in bearings.

NOTE: It is accepted that in assessing the benefit of health monitoring, absolute proof is not possible, and reliance must be placed on engineering judgement and previous experience combined with sound design and test philosophies.

---

* As contained in Paper G778

2.5.2 In cases where a safe life is submitted, means shall be provided to monitor deterioration relevant to the achievement of the stipulated life.

2.5.3 In cases where the damage tolerance characteristics are claimed, the effectiveness of the health monitoring technique for detecting damage in time to enable the Safety Assessment criteria to be met shall be established. This must take into account the reliability of the health monitoring equipment."

The following new Supplement will be proposed for addition to Chapter A6-4

"SUPPLEMENT NO. 4 TO CHAPTER A6-4

HEALTH MONITORING - HELICOPTER ROTOR AND TRANSMISSION SYSTEMS

1 APPLICABILITY

The requirements of this A6-4 Supplement No. 4 are applicable to Helicopters where credit has been claimed for the detection of incipient failures by the use of health monitoring techniques.

Credit may be claimed in respect of:-

(a) establishing compliance with the Safety Assessment criteria in G4-9, 2.5.

(b) providing the means of preventing the failure of a critical component.

(c) establishing justification for extending overhaul periods.

NOTE: Rotor/Transmission overhaul periods, and sampling intervals will be restrictive unless effective health monitoring methods are practised to control critical failures which are not directly age related.

2 RESPONSIBILITIES

The responsibilities of the helicopter constructor (the Constructor) and the Operator in complying with 1 shall be as prescribed in 2.1 and 2.2 respectively.

2.1 The Constructor

The Constructor shall:-

(a) identify critical components dependent on health monitoring for integrity,

(b) establish a programme for monitoring the condition of critical components at prescribed intervals, and

(c) take account of the evidence from 2.2(b) in the strength substantiation of critical components.

2.2 The Operator

The Operator shall:-

(a) ensure that the components identified in 2.1(a) are subjected to an effective health monitoring programme in accordance with a programme agreed by the Authority and based on the manufacturers' recommendations for the detection of deterioration before failure occurs,

(b) inform the manufacturers of any damage or wear found on critical parts during any inspections,

(c) publish in the Maintenance Programme (A6-4.2) details of the health monitoring programmes, including the techniques and methods of data collection, interpretation and implementation and individuals' responsibilities."

The following new Appendix to Supplement No. 4 is proposed for Chapter A6-4.

"APPENDIX TO SUPPLEMENT 4 TO CHAPTER A6-4

1 RESPONSIBILITY OF THE OPERATOR (See A6-4 Supplement No. 4, 2.2(a))

1.1 An effective health monitoring programme requires that:-

(a) the manufacturers' recommendations are satisfied,

(b) there is a management commitment to the practice,

(c) the associated skills and techniques are systematically developed, and adequate facilities made available,

(d) individual responsibilities are defined and sufficient to ensure timely analysis and implementation of corrective actions, and

(e) all relevant service experience is reported to the Constructor."

HEALTH MONITORING WORKING GROUP

MAINTENANCE REQUIREMENTS

These notes summarise the existing requirements, those in draft and those under consideration which have been reviewed in terms of being adequate to cater for future Health Monitoring equipment and installations.

Additionally, the possible implications in respect of the MMEL have been considered.

1 Current BCAR A3-3, Airframe Parts and Equipment

Part of the procedures whereby installations designed by CAA Approved Organisations, are approved/accepted by the CAA, require that Maintenance, Overhaul, Repair and Installation Manuals are produced/provided where appropriate.

2 Current BCAR A6-2/A6-4, Maintenance, Overhaul and Repair Manuals

The constructor/manufacturer is required to produce acceptable manuals containing information for the maintenance, overhaul and repair of aircraft, including engines/APUs, propellers, components, accessories, equipment, instruments, etc, and their associated systems, for aircraft to be granted any category of UK C of A.

For Transport Category aircraft the applicant/operator shall submit his maintenance schedule/programme to the CAA for approval. Such schedules/ programmes shall contain at least the following:-

a) Periods at which the item shall be inspected, together with the type and degree of inspection.

b) Periods at which the item shall, as appropriate, be checked, cleaned, lubricated, adjusted and tested.

c) Periods at which the item shall be overhauled or replaced by a new or overhauled item, expressed in terms of:-

- a criterion related to usage, eg a period of time, number of cycles, number of landings;
- a criterion related to condition, eg limits of wear, limiting dimension.

NOTE: Where actual criteria are not included in the Schedule, they should be defined by cross-reference to acceptable documents, eg Approved Maintenance Manuals.

d) The Mandatory Life Limitations to which certain parts of aircraft, engines, propellers, auxiliary power units and systems, the failure of which could have a hazardous effect on the aircraft, are subject. For foreign products these limitations, unless otherwise agreed by CAA, shall be identical with those specified in the mandatory life limitations section of the manufacturer's recommended Maintenance Schedule (see A6-2, 4).

e) Such other processes as are agreed by the CAA, eg condition monitoring.

3 Final Draft Paper A46 - BCAR A2-1 and A6-4, New Supplement No 2

A revised A2-1 will require a Maintenance Review Board (MRB) to be established for all new Transport Category aircraft above 5700 kg and others as deemed necessary by the CAA. The new Supplement No 2 to A6-4 gives the detail of the MRB process which requires analysis of systems etc to assign maintenance/operational tasks and intervals. Additionally, it is required to identify those tasks which analysis has shown to be safety related.

4 Loss of Essential Airworthiness Function Prevention Programmes

Provisional work is well advanced which, if accepted as policy, will require that, for all aircraft certificated under FAR/JAR 25.1309 conditions, an in-service monitoring programme be established.

Namely, all operators will report to the constructor all events, defects, maintenance findings, etc that have been identified by the Safety Assessment as those that could lead to a loss of essential function if their rate of occurrence is not contained within acceptable limits.

5 MMEL

Current consultative proposals for the 'formalised' introduction of MMEL's will require the constructor to provide an MMEL only for aircraft above 8000 kg. The CAA will now be required to approve MMEL's.

Consideration should be given to the need to establish requirements such that Health Monitoring equipment is reflected in Flight Manuals/MMEL's for rotorcraft below this proposed 8000 kg weight limit.

APPENDIX 6

HEALTH MONITORING RESEARCH AND DEVELOPMENT - MINISTRY OF DEFENCE

Related Ministry of Defence Reports in preparation under Naval, General and Air Staff Target 6638 - Vibration Monitoring:

1 Stewart Hughes Ltd, Southampton

a) Helicopter Transmission System Diagnostics

b) Intershaft Bearing Damage Detection

c) Helicopter Rotor Fault Diagnosis Study

2 Westland Helicopters Ltd, Yeovil

a) NGAST 6638 support contract (includes vibration signature vs gearbox build variations).

Additional Report:

Stewart Hughes Ltd : Report No SHL 162 February 1985

'Monitoring of Rotorcraft Dynamic Systems'.