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HELICOPTER HEALTH MONITORING

Operational Trials Review

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This Paper reviews the Bristow Helicopters Super Puma and British Helicopters S61N helicopter health monitoring operational trials which were carried out between 1986 and 1991 as part of a helicopter safety research programme which was jointly funded by CAA, the UK Offshore Operators Association and the UK Departments of Transport and Energy (now HSE).

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Contents

1 INTRODUCTION

Early in 1983, at the request of the Chairman of the CAA, the Airworthiness Requirements Board (ARB) established a Panel to review existing airworthiness requirements for public transport helicopters taking account of associated operating practices, and to recommend changes to ensure that the safety standards of these aircraft matched more closely those of comparable fixed-wing aircraft. The background to the request to the ARB was a growing unease with the safety record of helicopters, not only in the CAA but more widely. The predominant helicopter operation in the UK was then, and still is, in support of the oil and gas fields in the North Sea. However increased use for more conventional public transport applications, such as commuter or city-centre to city-centre operation, was then considered likely. As it happens, there has in the interim been little increase in this type of operation worldwide, and no increase in the UK.

This Panel, the Helicopter Airworthiness Review Panel (HARP) reported in 1984 and its report (Ref.1) made a number of recommendations which were accepted in full by the ARB and the CAA. Three of the recommendations referred to health monitoring and led to the formation of the Health Monitoring Working Group in March 1984. This Group's report (Ref.2) examined in detail all aspects of helicopter health monitoring and amongst its recommendations was a call for in-service trials to promote health monitoring (Ref. Appendix 1 for Summary of the Report).

The technical recommendations made by both the HARP and the Working Group were, necessarily, in rather general terms and needed research before regulatory action could be formulated. A comprehensive post-HARP research programme was defined in 1985 and a considerable impetus was given to this proposed work when, in 1986, the UK Government (Departments of Transport and Energy) and Industry (the United Kingdom Offshore Operators Association, UKOOA) agreed to join the CAA in funding the £1.6m research programme. This programme included work on transmission and rotor system health monitoring, crashworthiness, ditching, damage tolerance and some flight related subjects.

The operational trials of health monitoring systems were carried-out between 1987 and 1991 by two UK based helicopter operators, Bristow Helicopters Limited (BHL) and British International Helicopters Limited (BIHL) using Aerospatiale AS332L Super Puma and Sikorsky S61N helicopters respectively in normal North Sea oil/gas rig support operations. These trials were aimed at demonstrating the suitability, reliability and credibility of prototype systems and are the subject of this Review Document. The effectiveness of health monitoring techniques to identify defects was not assessed during these trials.

At the completion of most of the research projects, CAA issued a Discussion Paper in November 1989 on 'The Airworthiness of Group A Helicopters' (Ref.4) which outlined the progress made on all the projects, including the operational trials which were still running, and sought comments from industry on proposed changes to design standards prior to any formal consultation process. This Review Document consolidates and supplements information provided on the trials in the Discussion Paper.

It was agreed in 1990 with the same funding partners that a further 3-year follow-on research programme was required to address a number of outstanding items from the initial programme. The most significant item of this follow-on research programme was the demonstration by seeded-fault gearbox tests at representative powers of the effectiveness of health monitoring techniques to identify defects before they developed into catastrophic failures and also to investigate defect propagation rates. The results of these tests would complement the earlier operational trials and allow CAA to more fully assess the safety benefits that could be attributable to health monitoring systems. This seeded-fault gearbox test programme commenced in 1991 with Westland Helicopters Limited (WHL) and Eurocopter-France (ECF) using S61 and Super Puma main rotor gearboxes respectively and should be completed in 1994.

This Review Document gives a brief description of the BHL and BIHL helicopter health monitoring operational trials and summarises the results and conclusions obtained from the trials. It also presents the CAA assessment of the conclusions and clarifies the current position on a number of design and certification issues. For a more detailed description of the two trials, CAA has separately published both the BHL and BIHL trial reports (Refs 5 and 6). A similar Review Document and associated Company test reports will be issued in 2 to 3 years to cover the current seeded-fault gearbox test programme.

2 HEALTH MONITORING – BACKGROUND

Health monitoring is, in general terms, the process used to detect deterioration in an assembly or component (Ref.7). To be effective it relies on a physical change being present for a sufficient length of time to permit detection of the deterioration before failure occurs. The concept of health monitoring is not new to helicopters because gearbox oil temperature and pressure indicators/warnings and magnetic chip detectors are all health monitoring techniques that have been employed for many years.

Health monitoring exploits the time available before failure resulting from any damage tolerant characteristics inherent in the design, and it follows that, for maximum benefit, damage tolerance must be a design criterion. This may be achieved by redundancy within the assembly or component but in other cases there may well be a limited period for detection as a failure develops, provided the propagation is slow.

The CAA implemented a HARP recommendation by forming a Working Group on Helicopter Health Monitoring. The Group published a report in August 1984 (Ref. 2 and Appendix 1) and, amongst its findings, endorsed the view that the rotor and transmission systems would receive major benefit from the application of health monitoring techniques. A range of potential techniques was summarised in the paper, and recommendations made for further research and development.

Although a number of health monitoring techniques were identified, the gearbox vibration monitoring techniques then under development promised to detect potentially catastrophic failures in the most critical components in the transmission system. In addition, a variety of oil analysis techniques were identified as being useful in detecting wear and other deterioration in major components and bearings. Failures in transmission system critical components were more likely to result in serious fatal accidents (i.e. total loss of life) than failures in any other helicopter mechanical components.

Coincident with the developing gearbox vibration monitoring techniques was the introduction of digital flight data recording (DFDR) systems to helicopters. Prior to 1980, the helicopter had not been an ideal airborne platform for the flight data recorders then available. However, with the advent of integrated digital electronic systems which could withstand the helicopter's harsh operating environment it was demonstrated in the early 1980's to be feasible to install DFDRs onto civil helicopters, primarily for accident investigation purposes. With the prospect of the mandatory carriage of DFDRs on public transport civil helicopters and the recording systems for health monitoring techniques being similar to DFDRs, health monitoring was much more likely to gain support from the helicopter manufacturers, operators and users, particularly for the potential airworthiness, operational and economic advantages that it could offer. To prove the feasibility of fitting health monitoring onto conventional civil helicopters an operational trial was set up, with the dual purpose of also providing to industry a convincing demonstration.

This Paper summarises the results of the most comprehensive operational trial of helicopter health monitoring techniques carried out to date. As a result, CAA has now established helicopter safety objectives and developed and published design requirements for new helicopter certifications (Ref. 3) which reflect the potential to enhance safety with health monitoring.

3 HELICOPTER SAFETY OBJECTIVES

A study carried out by a HARP sub-committee concluded that the fatal airworthiness accident rate for large twin engined helicopters was greater than that for comparable fixed wing aircraft. This conclusion was based on the UK rate of approximately 50×10^{-7} per flight hour for large helicopters at that time which, by the late 1980's, had improved to approximately 30×10^{-7}.

Studies in the late 1980's estimated fatal airworthiness accident rates for fixed wing aircraft in all types of operation world-wide to be:

Light Twins	16×10^{-7} per flight hour
Commuter turboprops	11×10^{-7} per flight hour
Large turboprops	6×10^{-7} per flight hour
Small jets	5×10^{-7} per flight hour
Large jets	1×10^{-7} per flight hour

This data confirmed that the fatal airworthiness accident rate for large helicopters was significantly greater than for transport aeroplanes.

Against this background, the CAA adopted in its BCAR 29 design requirements (Ref. 3) the safety objective for a Group A rotorcraft as being 'the probability of occurrence of failures from all causes that would prevent safe flight and landing is Very Remote' and Very Remote was to be interpreted as being less probable than 10^{-6} per hour of flight. The effect of this requirement should be to bring helicopters of new design up to the level currently being achieved by turboprop aircraft of comparable size, but generally older design. However, they will still fall somewhat short of the levels currently achieved by the larger jet transport aircraft, many also of older design.

HARP concluded that the principal source of critical single failures in helicopters was in the rotor and transmission system, ie. the rotating machinery. The dominant nature of these failures when compared with those of all other helicopter systems caused CAA to adopt 'Very Remote' as a discrete objective for the rotor and transmission system. Unless significant improvements were made to the rotor and transmission system it would be unlikely that a new but conventional design helicopter could meet the overall safety objective without the exploitation of health monitoring.

4 HEALTH MONITORING – DESIGN REQUIREMENTS

For helicopters, the UK certification standard has been BCAR Section G and more recently BCAR 29. This is to be superseded by the new JAR 29 when published in 1993. The new safety objectives have been defined (see para. 3) and the requirements call for a safety assessment of the rotor and transmission system including a detailed failure analysis to confirm the inherent safety level of the design by identifying critical parts and the compensating provisions that give assurance to the low probabilities for failure required of them.

The requirements do not state that health monitoring techniques must be employed; it is the safety assessment that establishes this need. Provision is, however, made for the applicant to seek credit for them and this provision requires that the credit for such techniques must be substantiated. It is accepted that the credit cannot be absolutely quantified – at best it is possible to establish a level of confidence which will be substantiated by engineering judgement, sound design and testing, and from previous service experience. This would be confirmed by future service experience. This principle is not new, it is used in virtually every aspect of the certification process. It is clearly a significant benefit to conduct the development/certification programme with the health monitoring systems fitted, and furthermore to integrate the monitoring philosophy with the design of the rotorcraft.

The success of a health monitoring programme is also dependent on making full and proper use of the information in a timely manner. The CAA would therefore need to be satisfied with a company's management commitment for each programme. This would start with documented company procedures defining individual responsibilities and associated skills, techniques and facilities. This would establish the commitment to the integration of health monitoring into the Maintenance Programme to maximise safety.

Retrospective requirements are in preparation and will be proposed once the new large helicopter design requirements are published in JAR 29. It is anticipated that new design requirements will become retrospectively applicable by 1995.

5 HEALTH MONITORING – RESEARCH PROGRAMME

The post-HARP research programme which commenced in 1986 explored various potential health monitoring techniques selected from a range offered for consideration by the Health Monitoring Working Group. The programme was structured to explore the potential of some longer term projects as well as those techniques sufficiently advanced to be fitted to current helicopters for operational trials. From the range offered for consideration the following nine were selected for further examination:

1 Expert systems
2 Fibre-optic crack and strain sensors
3 Advanced Health and Usage Monitoring System (HUMS) computing requirements
4 Frequency Modulation telemetry torque meter
5 Bearing vibration analysis
6 Rotor track and balance data handling
7 Spectrographic Oil Analysis Programme (SOAP) and wear debris
8 Supa Puma health monitoring operational trial
9 S61N health monitoring operational trial

All these projects have previously been described in a CAA Discussion Paper (Ref.4). This review document examines only those projects connected with the health monitoring operational trials (ie. items 6 through to 9).

6 HEALTH MONITORING – OPERATIONAL TRIALS

The primary objective of the operational trials was to investigate the suitability, reliability and credibility of health monitoring techniques during an in-service trial using typical oil/gas industry support helicopters in the rigorous operational environment of the North Sea and to determine how the results of such health monitoring systems could be integrated with the maintenance function.

CAA contracts were placed with two major UK helicopter operators, Bristow Helicopters Ltd (BHL) and British International Helicopters Ltd (BIHL) to act as programme managers for the trials. Both trials had similar objectives but employed quite different health monitoring systems, aircraft and techniques.

6.1 Bristow Helicopters Ltd (BHL) AS332L Super Puma Trial

The CAA contract was placed on 17th July 1987 with BHL as programme managers and with Smiths Industries (SI), Westland Helicopters Limited (WHL), and MJA Dynamics Ltd (MJAD) as major subcontractors. SI provided the major airborne hardware, WHL provided the transmission vibration monitoring technology while MJAD developed rotor system diagnostics. A summary of all the participants and their role is shown in Appendix 2.

During the 3 year trial, which commenced in mid 1987, the following techniques were investigated:

(1) Gearbox vibration monitoring – Analysis of accelerometer data

(2) Oil analysis (off-aircraft) – Spectrographic Oil Analysis Programme (SOAP)
– Wear debris monitoring

(3) Oil analysis (on-aircraft) – Quantitative Debris Monitoring (QDM)

(4) Main rotor track and balance – Automatic acquisition of data

(5) Airframe vibration – Automatic acquisition of data

(6) Monitoring of control loads and critical bearing temperatures

Up to five Super Puma aircraft were involved in the initial gearbox vibration analysis development phase of the trial. Following this, two aircraft were equipped with the full airborne system (see Fig. 1) at any one time and flew a total of 2091 monitored flight hours mainly on normal revenue services from Aberdeen Airport, Scotland to the UK North Sea sector. Engineering support was provided by BHL at Redhill, WHL at Yeovil, SI at Basingstoke and MJAD at Southampton. The trial was completed on 15th June 1990.

6.2 British International Helicopters Ltd (BIHL) S61N Trial

The CAA contract was placed on 7th March 1988 with BIHL as programme managers and with Hawker Siddeley Dynamics Engineering Ltd (HSDE) and Stewart Hughes Ltd (SHL) as major subcontractors. HSDE provided the major airborne hardware and SHL provided the transmission vibration monitoring software technology and ground based systems as well as trial support and analysis. A summary of all the participants and their role is shown in Appendix 3.

In addition to the funds provided by CAA/UKOOA/DOTp/DEn, the UK Department of Trade and Industry (DTI) provided funds to HSDE and SHL for hardware and software development.

During the 3 year trial, which commenced in early 1988, the following techniques were investigated :

(1)	Gearbox and bearing vibration monitoring	–	Analysis of accelerometer data
(2)	Oil analysis (off-aircraft)	–	Spectrographic Oil Analysis Programme (SOAP)
(3)	Oil analysis (on-aircraft)	–	Wear debris monitoring by a 'zapper' facility and by magnetic plugs
(4)	Main rotor track and balance	–	automatic acquisition of data
(5)	Tail rotor balance	–	automatic acquisition of data
(6)	Engine power checking, usage and exceedances		

Two S61N aircraft were equipped with the full airborne system (see Fig. 2) in October 1989. The first year of the trial was, essentially, development flying while the second year was devoted to the commissioning and to the full operational trial. At the completion of the operational trial in early September 1991 a total of 1887 monitored flight hours had been accumulated mainly on normal revenue services from Sumburgh Airport, Shetland to installations in the East Shetland Basin of the Northern Sector of the UK North Sea. Engineering support for the trial was supplied by BIHL at Aberdeen, SHL at Southampton and HSDE at Welwyn Garden City.

BIHL were project managers for the trial and were responsible for the day to day control of the trial. They also carried out the design, certification and installation of the aircraft cable looms and equipment.

HSDE and SHL were jointly responsible for the development of the health monitoring system. HSDE developed the engine monitoring and airborne data management sub-system and produced the airborne equipment. SHL developed the vibration monitoring sub-system of the airborne equipment and provided the ground based systems. Although engine health monitoring was installed on the S61Ns, it was not included in the CAA trial and, therefore, has not been covered in detail in this Review Document.

6.3 Timescales and Manhours

In both trials there was a considerable overrun on the original timescales. What initially seemed possible within 2 years, actually took 3 years to complete. This was no reflection on the professional capabilities of the companies concerned but was the inevitable consequence of companies underestimating the resources required and changing their commercial strategies, staff and operational changes, and the complex technical problems of introducing new-technology in a harsh operational and economic climate. In addition, the trials were expanded by CAA to include additional aircraft in the operational trial.

Manhours expended on both trials were also far greater than originally estimated. Both trials had, typically, 3 to 5 full-time staff dedicated to the trial for the whole period. However, before the end of the trials, both companies were also devoting considerable effort to the development and demonstration of production integrated FDR/HUMs systems to meet CAA's mandatory date for the installation of FDR's on public transport helicopters.

In spite of these and many more problems, both trials were successfully completed in 3 years and comprehensive reports were issued by both companies (Refs. 5 & 6).

7 HEALTH MONITORING – TECHNIQUES EMPLOYED IN TRIALS

7.1 Gearbox Health Monitoring

A typical helicopter main rotor gearbox can experience a number of different types of mechanical failures. Many are fatigue related structural failures of gear teeth, webs, shafts or bearings. Others are wear related caused by contact fatigue (pitting) or by lubrication related problems (scuffing). The monitoring of these incipient failures can be carried out by two complementary health monitoring techniques: vibration monitoring and oil debris monitoring. Both these techniques are capable of identifying different types of failure modes (eg. vibration monitoring can detect fatigue failures, oil debris monitoring can detect fretting and spalling) and both were evaluated during the operational trials.

7.1.1 *Gearbox Vibration Monitoring*

Both trials employed gearbox vibration monitoring techniques which derived raw vibration data from a number of strategically mounted gearbox accelerometers. Using this data and a tachometer signal obtained from an optical or magnetic sensor mounted on one of the shafts in the drive train, gear vibration signatures are produced using a time domain signal averaging process which, after a number of summing operations, eliminates known gearbox signatures but retains abnormal vibration information.

This signal averaging process is repeated for each gear shaft in the gearbox producing a set of signal averages, each unique to a particular shaft (see Figure 3).

The signal averages are generally too complicated for visual interpretation, so they are further processed using algorithms specially developed to highlight types of failures. The diagnostic capability of the signal averaging process is critically dependent upon the method of enhancement (ie. the suite of algorithms used) as well as the parameters and attendant thresholds that are subsequently applied.

(a) BHL Super Puma Vibration Monitoring Technique

The BHL trial employed a vibration technique developed by WHL and previously trialed on military helicopters. Indicators used for the airborne trial were specifically developed by WHL for the Super Puma using raw data obtained over some 253 flights covering approximately 10,900 flying hours during which TEAC analogue tape recordings and SI's Vibration Analysis System (VAS) recordings were made.

The technique took the raw signals from accelerometers mounted on the gearbox being monitored (see Figure 4) and performed a number of calculations to average and enhance the signals so as to provide three quantitative indicators relating to the health of each shaft and gear. The indicators were M6*, peak to peak ratio, and standard deviation ratio plus 'development' algorithms for shaft and gear eccentricity and mesh frequency amplitude.

Twenty two shafts/gears were monitored on the Super Puma using nine accelerometers (Endevco 7251-10). Seven accelerometers were mounted on the main rotor gearbox at positions defined by WHL. Three of these were sited to monitor the two epicyclic gear stages. The remaining two accelerometers monitored the intermediate and tail rotor gearboxes.

For the operational trial of the full airborne system, the HUM computer (SI 0854KEL) and other airborne trials equipment were mounted in a half ATR box in a special cabinet on the floor of the forward left-hand side of the passenger cabin (see Figure 5).

A single recording of vibration was taken once during each flight over a 3 minute period at 62% torque in cruise. Unless the data was downloaded at the end of each flight, the previous recording was lost. Processing was carried-out in-flight and analysis was entirely ground based following downloading of the data, typically at the end of a day's flying, to a ground based computer. This procedure could give an indication of a detectable defect between flights, dependent on aircraft downtime. The trials specification called for the equipment to be capable of on-board analysis and interrogation by the crew using a Control Display Unit (CDU) on the flight deck, but this facility was inhibited for the trial by CAA because no credit was to be given to the health monitoring system by the crew during the trial. (See paragraph 8.1 for BHL functional description).

(b) BIHL S61N Vibration Monitoring Technique

The BIHL trial employed a vibration technique developed by SHL. This comprised a suite of diagnostic indicators derived from the analysis of the signal averages and related to a range of gear and shaft faults.

The SHL suite of indicators covered two categories of analysis:

- Levels – the measure of absolute or relative energy levels of tones or frequency bands within the signature
- Patterns – the search for various patterns in the vibration signature which can be associated with different faults. The pattern indicators are SHL's non-dimensional 'FM' numbers.

All the SHL indicators implemented during the S61N trial are shown on Figure 6. Pattern indicators are detectors of the presence of a fault, while vibration energy measurements provide additional information on the fault severity.

During the trial it was intended to carry out vibration monitoring of rolling element bearings (FM5) and to develop a new technique for epicyclic gears (FM6). However, neither of these techniques became available.

A total of nine accelerometers (Endevco 7251-10) were fitted to the trials aircraft; 7 mounted on the main gearbox (see Figure 7), and one on both the intermediate and tail rotor gearbox. Three tachometers were fitted, one each on the main rotor, tail rotor and the main gearbox. Data sampling was continuous and on-board analysis was used to sift and reject information which was not significant. The on-board analysis carried out by the Main Processing Unit (MPU) could provide 'go/no go' information between flights but it was necessary to use a Data Retrieval Unit (DRU) to download the data to the ground station for further analysis and to access the 'go/no go' results from the on-board system. (See paragraph 8.2 for BIHL functional description).

For the operational trial, the on-board recording equipment was located in a specially modified part of the aft baggage bay (underfloor at the passenger entry door threshold). Data downloading using the DRU was carried-out from the left-hand bulkhead aft of the flight-deck.

7.1.2 *Oil Debris Analysis*

Both trials employed various on-aircraft and off-aircraft oil debris analysis techniques with the objective of comparing their technical and operational performance. The techniques employed in the trials are briefly described below.

(a) Spectrographic Oil Analysis Programme (SOAP)

This off-aircraft laboratory technique evaluates the elements present within an oil sample taken from a gearbox by burning the oil at extreme temperature (some 10,000 deg C) and measuring the light spectrum emitted. It is capable of detecting extremely small (ie. well below one part per million) concentrations in oil of the following metallic elements:

(1) Iron (Fe)
(2) Chromium (Cr)
(3) Aluminium (Al)
(4) Copper (Cu)
(5) Silver (Ag)
(6) Nickel (Ni)
(7) Titanium (Ti)
(8) Silicon (Si)
(9) Magnesium (Mg)
(10) Tungsten (W)

This technique was employed during both BHL and BIHL trials.

(b) Particle Quantifier (PQ)

This off-aircraft technique uses a magnetometer type of equipment and provides a coarse indication of wear debris in oil samples, giving an empirical value, the PQ Index. This Index is a trending indicator and it is possible to use a portable analyser for use away from a laboratory. This technique was employed during both BHL and BIHL trials.

(c) Rotary Particle Depositor (RPD)

This off-aircraft technique extracts debris from a sample by a combination of magnetic, centrifugal and gravitational forces. Debris is left as a deposit on a glass side, suitable for microscopic examination to classify the amount and type of debris present, i.e. nonferrous cutting wear, fatigue chunks. The technique requires laboratory conditions and the results are subjective without numeric values. This technique was employed during both BHL and BIHL trials.

(d) Chip Detectors

This on-aircraft technique was available in two forms; the electric chip detector and the Tedaco 'Zapper' fuzz burner chip detector. The former counted chips considered as significant sized particles which bridged the gap of the detector. The latter removed by capacitance discharge at the detector gap, the fine dustlike wear particles or fuzz as they accumulate on the detector. Both chip and zapper discharge counts are recorded and give 'go/no go' indication. This was only employed during the BIHL trial.

(e) Full-flow debris monitoring

On-aircraft full-flow debris monitoring systems offer the potential to measure varying sizes of debris, count the number of chips/debris, discriminate between ferrous and nonferrous metals and to be easily adjusted to cater for different alert levels. The techniques are proprietary and vary from one manufacturer to another but the sensor would be installed in the helicopter's gearbox lubrication system so as to directly monitor the debris contained in the circulating oil flow. This was only employed during the BHL trial.

7.1.3 *Gearbox Strip-down Report*

At the completion of the trials, main rotor gearboxes were to be removed for overhaul and subjected to a detailed strip examination to correlate the results of the monitoring techniques with physical inspections.

7.2 **Rotor Track and Balance (RTB)**

7.2.1 *Rotor Vibration*

There are three main sources of rotor induced helicopter vibration:

(a) Main Rotor once-per-rev vibration (1R)

This vibration is produced by differences between rotor blades such as minor variations in weight, centre-of-gravity, twist, contour and stiffness. 1R vibration can be controlled and minimised by taking rotor track and balance measurements and making adjustments based on these. Track measurements are the relative height and lead/lag of individual rotor blades during a ground run or in flight. Balance measurements are the amplitude and phase of main rotor 1R vibration in vertical and lateral directions. Main rotor adjustments may include individual blade pitch link adjustments, weight adjustments, sweep and trim tab adjustments. Where 1R vibration levels cannot be reduced by these adjustments the cause of the vibration could be wear or damage of rotor head components (e.g. wear of pitch link bearings or loss of performance of lead/lag dampers).

(b) Tail Rotor Vibration

Although not always felt in the cockpit, a high tail rotor imbalance can, if not corrected, lead to structural damage of the tail boom.

(c) Blade passing frequency vibration (NR)

This is produced by the structural dynamic response of the rotor blades to the time varying air loads produced in forward flight which generally increase with load and airspeed. The sum of the individual blade responses produces hub moments and shears which excite airframe vibration.

7.2.2 *RTB System*

The condition of in-service helicopter rotor systems can be monitored using specialised RTB equipment, typically Helitune, Chadwick or SHL RADS. These maintenance methods can detect rotor mass imbalance, blade tracking and general airframe vibration levels and are usually employed when a problem is reported by the helicopter's operating crew. A problem with the current method of taking a 'snapshot' of the RTB during maintenance is that it takes no account of the considerable variation in a helicopter's weight during operation – RTB work may be carried-out at an AUW of 16,000 lbs while typical operational weights may be more than 18,000. Also consistent interpretation of RTB results by different line engineers may be difficult and dedicated RTB work is very expensive and time consuming.

Both BHL and BIHL trials fitted RTB sensors to automatically record the true conditions experienced during operational service. The BIHL trial continuously monitored main and tail rotor balance and, when indicated from this balance data, main rotor track data was acquired from an optical sensor. The BHL trial used RTB data to assess if it was possible to identify incipient failures as well as the usual maintenance actions.

RTB airborne equipment typically comprised a passive optical sensor with day only capability and airframe mounted accelerometers. Data outputs would be stored in the airborne computer and downloaded for ground analysis to give general trend information and maintenance alerts.

For the BHL Super Puma trial, a suite of software codes were written by MJAD to troubleshoot RTB maladjustments (eg. pitch link, blade tab and mass imbalance) as well as non-adjustable faults (such as mismatched lag dampers). The software codes could also predict the improvements to be expected following adjustment.

7.3 Other Techniques

The following additional monitoring techniques were evaluated during the operational trials :

7.3.1 *Airframe Vibration*

The airframe vibration signature is composed of a number of harmonics, one of which is associated with the blade pass frequency. Numerous airframe related faults can give rise to excessive airframe vibration (e.g. loose cowlings/access panels and loose sponson attchments). For the BHL trial, 3 accelerometers were fitted, one under the co-pilot's seat and two in the avionics cabinet, and the data was recorded by the airborne computer for later ground analysis.

7.3.2 *Control Load Measurements*

Numerous serious incidents have occurred resulting from failures in helicopter control systems. It was decided to attempt to monitor in-flight control loads in components during the BHL Super Puma trial and eight strain gauges were fitted at the following locations:

1 on each servo on the main gearbox (3 off)

1 on each main gearbox support strut (3 off)

1 at fuselage frame 9000

1 at the tail gearbox servo linkage

The signals from the strain gauges were recorded on the airborne computer and downloaded together with all other health monitoring data.

7.3.3 *Bearing Temperature Monitoring*

As tail rotor driveshaft support bearings have been known to fail in the past, BHL evaluated a bearing temperature monitoring technique. Six thermocouples, one on each of the tail rotor drive shaft bearing housings, were installed on the Super Puma and time in temperature band signals were recorded on the airborne computer and downloaded together with all other health monitoring data.

7.3.4 *Engine Health Monitoring*

The CAA health monitoring operational trial did not formally cover engine health monitoring because CAA's primary objective was to seek airworthiness improvements in the rotor and transmission systems and not the engines. However, for record purposes, a brief description of the BIHL/HSDE engine health monitoring system is included.

(a) Power Assurance Checks (PAC)

Power Assurance Checks (PAC) provide an indication of the ability of each engine to deliver sufficient output power under specified operating conditions.

It is important to know that the engines are capable of delivering their specified performance levels otherwise safety and fuel consumption can become impaired. Constant flying over open sea exposes the engines to salt spray ingestion, which can rapidly reduce the efficiency of the engines. Daily compressor washes are required to flush away the salt deposits and maintain engine performance. Other factors also reduce engine operating efficiency throughout its life; hence the need for regular Power Assurance Checks.

The PACs are performed for each engine in turn, at the beginning of each day's flying, whilst the engine is operating at 'cruise' power levels.

The following parameters were recorded to perform the PAC function:

Engine torque (Tq)
Power turbine inlet temperature (T5)
Gas generator speed (Ng)
Pressure altitude (ALT)
Outside air (intake) temperature (T2)
Free turbine speed (Nf), equivalent to rotor speed (Nr)
Air bleed status (AB)

(b) Topping

Topping checks provide confirmation that the required engine output power can be achieved at high power (2.5 minute one engine inoperative rating levels). The checks are conducted much less frequently than the PACs, for example when engine or fuel control system changes are made or some 450 flight hours have elapsed since the last topping check. The results are expressed in terms of a 'torque margin' which is the difference between the actual torque delivered and the expected engine torque, at the particular operating point. The topping function uses the same input parameters as the PAC calculations.

(c) Low cycle fatigue

The rotating elements of gas turbine engines are subject to a number of stresses, one of which is fatigue induced by cyclic speed variations throughout the operation of the engine's life. A basic low cycle fatigue counting function was recorded for the gas generator spools on each engine.

(d) Limit exceedances

Limit exceedances for both engines and transmission total torque can be recorded. In addition to the PAC parameters engine lubrication oil temperature and for the transmission total torque (sum of the two engine torques) are recorded.

7.4 General Operational Statistics

In addition to the information recorded for health monitoring purposes, the trial showed that systems could record useful operational information, probably more reliably than operational flight crews. Examples of the parameters recorded were:

Number of successful engine starts
Engine run times
In-flight engine shutdown count
Engine run-down times
Number of take-off and landing cycles
Airframe hours

8 HEALTH MONITORING – FUNCTIONAL DESCRIPTIONS

Brief descriptions of the procedures/routines adopted by the two operational trials are detailed below.

8.1 BHL Super Puma Trial – Functional Description (See Figure 8)

Detailed below is the typical sequence of events that took place during the operational trial of a fully commissioned health monitoring equipped helicopter.

(1) Prior to each flight (note – a 'flight' is normally defined for North Sea helicopter operations as the flying that takes place from the departure from its base, ie. Aberdeen in this case, to its return, regardless of the number of offshore rig landings made) a HUMS Data Acquisition pro-forma was prepared by dedicated HUMS engineering staff and inserted into the aircraft's technical log.

(2) The pro-forma required flight-crew to acquire data by operating the CDU for:

- rotor track and balance on the ground in daylight in one defined condition for 30 seconds.
- rotor track and balance in flight in daylight in four defined conditions
- rotor transient conditions in flight in daylight
- dynamic control load measurement in straight and level flight at 62% combined engine torque
- gearbox vibration in straight and level flight at 62% combined engine torque maintained for 3 minutes. The on-board processing would take a further 20 minutes.

(3) After the flight, the pro-forma was returned to the HUMS engineers

(4) At the end of a day's flying, HUMS engineers downloaded data from the airborne HUM computer to a portable lap top computer. This operation required the aircraft to be supplied with uninterrupted ground power for 15 to 20 minutes for the download and a further 5 minutes for the oil analysis data download (Ferroscan system). Operational problems meant that this downloading took between 1 and 1.5 hours on each of the two trials aircraft at particularly unsocial hours.

(5) HUMS engineers then loaded the data into the ground based computer for further analysis and archiving. The data was analysed using a WHL fault matrix and if any problems were identified by BHL they consulted specialist staff at WHL for advice.

(6) Rotor track and balance data was transferred to MJA Dynamics for diagnostic development and analysis.

8.2 BIHL S61N Trial – Functional Description (See Figure 9)

Detailed below is the typical sequence of events that took place during the operational trial of a fully commissioned health monitoring equipped helicopter.

(1) The system automatically carried-out vibration analysis once certain flight regime parameters were obtained (indicated airspeed, altitude and engine torque). This analysis was scheduled to take 18 minutes (to complete 19 individual gear/shaft analyses in sequence) and it would complete as many of these as time permitted. No specific tasks were required of the flight-crew of HUMS equipped trials aircraft.

(2) Data downloads were taken between flights by a dedicated HUMS engineer. This took place both during turnaround and at the end of a day's flying at Sumburgh. Download from the airborne MPU computer to the hand held DRU took, typically, 2 minutes and required only aircraft internal battery power. No specialist skills were claimed to be required to both operate and assess the DRU's displayed results.

(3) The DRU display was designed to indicate to flight line engineers whether the aircraft's transmission system was fit to fly.

(4) The DRU was downloaded to the ground station computer (GSC). This, typically, took 10 to 15 minutes after which the updated data base was available for analysis by a specialist HUMS engineer. The GSC's presentation was mainly of a menu driven graphical form with warning indications clearly identified.

(5) The GSC displayed usage data such as airframe hours and landings.

(6) SOAP and Swansea Tribology data was manually loaded into the GSC once the oil analysis results were available.

9 HEALTH MONITORING – TRIALS EXPERIENCE

The trials results are briefly summarised below. For a more comprehensive description of the results, reference should be made to the appropriate CAA Papers (Refs. 5 and 6).

9.1 BHL Operational Trial Experience

(a) Gearbox Vibration Monitoring

For the first year of the trial, BHL and WHL carried out an intensive development programme during which 71 test flights were flown to obtain the TEAC tape recordings from which WHL were able to develop algorithms specific to the Super Puma. This was followed by 182 downloads using an SI's VAS. Experience from this development work, involving five helicopters, led to the final definition of an operational system.

The operational system employed SI's 0854 KEL computer and acceptable downloads began to be made from June 1989. A total of 283 downloads covering 2091 flying hours were made up to the time the airborne trial of gearbox monitoring was completed in December 1989 (See Figure 10).

(b) Oil and Debris Analysis

In addition to the gearbox monitoring, some 344 oil samples were taken for analysis by 3 laboratories using 3 oil analysis techniques (SOAP, PQ and RPD). Analysis was carried out within 48 hours of receipt by the laboratory. Some 67 downloads of the Sensys 'Ferroscan' debris monitoring system were made.

(c) Rotor Track and Balance (RTB)

280 files of RTB data were collected for troubleshooting purposes.

(d) Other Techniques

The results for airframe vibration, control loads and bearing temperature monitoring are detailed in the appropriate CAA Paper (Ref.6).

9.2 BIHL Operational Trial Experience

(a) Gearbox Vibration Monitoring

Following 18 months of development work, flight standard computers were supplied by HSDE/SHL to BIHL in October 1989. Commissioning of the system using two S61N helicopters was completed in June 1991 at which time CAA had been satisfied that reliable, consistent and usable data was being generated after each flight. For CAA to be satisfied with the trial, at least 300 flight hours of post commissioning flying was required. This was achieved by September 1991 at which time a total of 1887 main gearbox monitoring flight hours had been accumulated. Soon after the trial was completed, one of the main rotor gearboxes was removed for overhaul and the gearbox strip report has confirmed that there was no significant defect in the gearbox.

(b) Oil and Debris Analysis

BIHL's standard practice was to take oil samples for SOAP analysis. During the trial, SOAP and Swansea Tribology samples were taken every 50 flying hours. On-line oil debris monitoring was carried out using the Tedeco 'Zapper' chip detector during the final 350 flying hours of the BIHL trial. No debris or evidence of discharge were recorded.

Detailed descriptions of the results obtained are contained in the appropriate CAA Paper (Ref.5).

10 HEALTH MONITORING – TRIALS CONCLUSIONS

10.1 General

10.1.1 The objective of the operational trials was to investigate and assess the suitability, reliability and capability of on-board health monitoring systems embodying advanced and enhanced health monitoring techniques when applied to helicopters in service over the UK North Sea. This objective has been met.

As an overall conclusion, it can be stated that the results from both trials demonstrated that various and significant health monitoring techniques can be successfully retrofitted to S61N and Super Puma helicopters and provide in-flight acquisition of data for the monitoring of rotor and transmission flight critical systems in every day flying operations over the hostile environment of the North Sea. Feasibility has been shown for the application of similar equipment to different helicopters without difficulty.

Although both systems trialled provided in-flight processing of acquired data, neither provided flight-deck warnings. The issue of flight-deck warnings was, therefore, not addressed during the trials (see paragraph 10.11.4).

10.1.2 The trials have demonstrated the suitability of certain techniques for use in the normal helicopter operating environment, whilst others require further development.

10.1.3 The trials have demonstrated that reliability levels for health monitoring system hardware and software may be anticipated to match those of other similar avionic and instrumentation equipment in helicopter applications subject to established disciplines for qualification, integration and maintenance practice being applied.

10.1.4 A health monitoring system's credit-worthiness, i.e. its capability in providing airworthiness or maintenance credits (benefits), could only be partially addressed by the trials. It is a composite of two essential ingredients – its reliability in routinely and consistently gathering good quality data and its effectiveness in analysing that data to highlight abnormality.

The reliability ingredient is now better understood but the effectiveness of the chosen techniques can only be validated by separate exercises involving helicopter constructor and technique specialists. It was never expected nor desired that failure cases would arise during the trials exposure.

Some techniques trialled, most notably vibration health monitoring of the transmission gearboxes, are established bench-proven technology However, some unknowns still exist for signature characteristics related to the propagation of typical defects at representative aircraft powers and further research is required for this and other techniques. (see Section 11 – Follow-on Research Programme)

10.2 Vibration Health Monitoring

It is the technology of advanced vibration monitoring of flight critical transmission elements (gears, shafts, etc.) that perhaps offers the greatest potential from a health monitoring system in enhancing safety. It promises the capability for monitoring for the myriad of failure modes for which there are unlikely to be warning systems other than subtle changes in their normal vibration signatures. For example, failure modes propagating through pure fatigue may never or only at their final stages shed debris capable of detection by magnetic plugs. For other critical parts that are not oil wetted and therefore probably not monitored by other means, vibration analysis may offer the only available protection.

10.2.1 For both trial systems, after periods for commissioning, the vibration analysis function for gearbox monitoring produced good quality data with consistency in results and sensitivities which gives confidence in the potential ability of bench established diagnostics to identify defects arising in-flight.

10.2.2 For both systems the vibration monitoring techniques were readily applied to the S61N and Super Puma transmission systems without undue aircraft type-specific adaptation and it is considered that they could therefore be similarly applied to different helicopter types.

10.2.3 For reasons of signature variability and stability both systems required that data be acquired, processed and analysed in a consistent flight regime (cruise).

10.2.4 One of the trial systems required that the flight crew initiate the acquisition of data when at a prescribed stabilised flight condition with the result that a high proportion of acquisitions were spoiled or were not initiated. Automatic acquisition of data is, therefore, considered to be essential and the system should be capable of recognising the prescribed flight regime and triggering the data sampling sequence. It is, however, beneficial for flight crew to still be able to initiate additional data acquisitions should he experience or suspect any abnormal conditions during flight.

10.2.5 Neither system provided a truly continuous monitoring function, one system gave a single 'snap shot' of data per flight for all shafts monitored, the other a number of sample points per shaft dependant on its sequencing routine and cycle time. One provided a single set of signal average signatures for further analysis on a ground station, the other favoured data compression to enable extra analysis points to be obtained. However, it should be remembered that both systems were demonstrators and reliably provided at least one sample point per flight for the WHL/SI system in the Super Puma and up to six analyses per flight per shaft for the HSDE/SHL system in the S61N prior to the trials being completed.

10.2.6 For both trial systems, a developing failure mode giving intermittent bursts of abnormal vibration signature, perhaps only during a transient flight regime would not be identified. Current technology that samples during defined stable flight conditions may not cater for such an event and further work is required should such failure modes be identified through service experience or failure analysis.

10.2.7 Validating the effectiveness of the algorithm suites in detecting failure propagation was beyond the scope of the trial. With the limited flight time exposures it was not anticipated that significant failures would occur – nor did they. For reasons of resourcing and time scales the full suite of diagnostic algorithms planned for embodiment in one of the trial systems was not implemented, specifically indicators for localised tooth damage of epicyclic gears and for rolling element bearing distress. Although judgements cannot be made for these, no special technical reasoning exists to suggest they would be less able than the other algorithms to be integrated into future health monitoring systems.

10.2.8 Both trial systems monitored the gear and shaft vibration characteristics for the main, intermediate and tail gearboxes. External shafts, most notably the tail rotor drive shafts and associated bearings, were not directly monitored. It is concluded that, because shafting internal to gearbox casings (being remote to sensing devices) can be discretely monitored, then such external equipment, where relatively short transmission paths exist, must also be capable of being monitored. However, whereas the gearbox casings provide a convenient gathering mechanism for the vibration signals, the monitoring of external shafting may well require a multitude of sensors carefully sited.

10.2.9 Health monitoring systems that require a degree of learning to redatum alert thresholds and criteria for individual units following maintenance actions (repair, modification, overhaul, installation etc.), should accomplish this process in a timely manner. During the interim period such systems should monitor on fleet type levels set to give an adequate level of confidence in fault detection. It is unacceptable to offer less protection than this for any interim period and any adverse effect on perceived false alarm rates must be accepted.

10.2.10 Both systems demonstrated the need and importance of carrying-out their own self test (BITE) alerting the maintenance staff of any problems and thereby reducing the number of spurious warnings to a minimum. This would have eliminated many hours spent identifying the cause of such spurious warnings in the HUMs computer, its sensors, etc. Without this, there will be the inevitable potential for loss of credibility from the user.

10.2.11 Due to the importance of the signal averaging process employed by both systems for data processing, the trials demonstrated the importance of procedures for built in warnings for processing failures, particularly where tachometer signal instability causes unacceptable variability in the results. The capability of a system to know its limits and to reject the analysis to try again later is of obvious advantage.

10.2.12 Both systems downloaded processed data to ground station computers for further evaluation. Both systems analysed data with predetermined algorithms (e.g. M6*, FM4) but only one system retained the basic signal averaged signatures for any future analysis work. Should analysis be desired by methods or techniques additional to those catered for then the existence of albeit pre-processed raw data is an advantage.

10.2.13 For the S61N health monitoring system, with its ability to vary the sequence that individual shafts were monitored, it was an advantage to include the high speed shafts twice within its schedule for reasons of successful data acquisition and the potential for rapid failure propagations where cycling rates are high.

10.3 Oil Wear Debris Monitoring

It has long been recognised that, for oil-wetted components, monitoring for wear debris shed through spalling, fretting or other wear mechanisms and transported by the oil provides a valuable diagnostic capability. Indeed most if not all helicopter types employ, at the very least, basic magnetic plugs. In recognition of their need for visual inspection these have been developed to provide electrical chip detection capable of flight-deck indication and, to discriminate between a chip and the build up of finer debris, some of these have the capability to burn off the 'fuzz' by means of a flight-deck switch. A chip would not be burned off and hence the flight-deck warning remains valid. Notwithstanding this evolution, current oil wear debris monitoring devices are unable to:

* Monitor the full flow of oil in circulation
* Discriminate between ferrous and non-ferrous debris
* Quantify the debris (for trend monitoring)
* Cater for debris sizes ranging from macro through micro to large chips in a single on-board technique.

10.3.1 *On board techniques*

(a) The Ferroscan full flow in line debris monitoring device included in the Super Puma trial, after much effort, was concluded to be unsuitable for helicopter applications without further development. This highlighted the difficulty of taking equipment from the bench or utilised on static engineering plant into the airborne environment without extensive flight development, manufacture and qualification to aerospace procedures/standards.

(b) The devices trialed were restricted to detecting ferrous particles only. To maximise health monitoring benefits, techniques that also offer the capability of detecting non-ferrous particles would be highly desirable and future development is needed in this respect.

(c) The S61N trials demonstrated that the Tedeco Zapper fuzz-burner chip detector could be satisfactorily retro-fitted to the S61N main rotor gear box and its output integrated into the health monitoring system. However, the adaptation of this military Sea King equipment in the civil variant was not without problems and highlighted the need for careful evaluation by the constructor or the operator's technical services before modification.

(d) Unlike most other techniques, monitoring for oil wear debris cannot be regarded as non-intrusive and the effects upon the system to be monitored must be considered (e.g. pressure drops, change of flow dynamics, etc.) as should any additional hazard potential they introduce (e.g. sensor integrity, o-ring-loss, etc.). To this end, any failure analysis conducted on the equipment to be monitored must also include the monitoring system.

10.3.2 *Off-line Oil Analysis techniques*

The oil medium not only transports the larger wear debris to sensors such as magnetic plugs, but also holds in suspension the finer macro or micro material. Such materials may give indication of critical failure mechanisms either at an early stage of development or for modes where one benign mechanism may lead to another of more serious effect. For example, frettage corrosion giving stress concentrations leading to failure by pure fatigue.

By drawing oil samples from trial main rotor gearboxes at approximately 50 flying hour intervals a number of techniques were investigated to compare their performance and correlate the results obtained with on-board gearbox health monitoring techniques. The techniques investigated were;

* Spectrograhic Oil Analysis Programme (SOAP)
* Particle Quantifier (PQ)
* Rotary Particle Depositor (RPD)

The following conclusions were drawn from these trials:

(a) Off-line oil sampling can be labour intensive and is sometimes seen as expensive in terms of direct cost. However, CAA believes from experience in other fields that this effort can be cost effective (extended time between overhauls, lower repair costs, etc.).

(b) The techniques trialed were most effective as trend indicators for which the management and presentation of the data base is important.

(c) The techniques were shown to give consistent results within a reasonable turn around time. Although operating from remote locations provisions were made for the effective transmittal of samples and timely return of information.

(d) No defects were highlighted on trials aircraft. However;-

  * For one trial operator, where SOAP is routinely employed on all their S61N helicopters, two main rotor gearboxes were rejected during the trial period (but not from trial helicopters). Strip evaluation confirmed wear at an early stage of development, not indicative of impending failure. The techniques were demonstrated to give corroborating evidence of damage development, and seen to be complementary by being sensitive to different sizes and types of debris.

  * For the other trial operator, strip examination of Super Puma gearboxes monitored during the trial identified minor bearing distress and it proved possible, with hindsight, to review the oil analysis records and identify some evidence of bearing spalling 50 to 80 hours before the failure was detected by the chip detector.

(e) Oil analysis, particularly SOAP, is used to good effect in modern fixed wing engine Condition Monitored Maintenance Programmes. However, understanding the constituent elements, their proportions and how the trends manifest comes through collaboration between constructor, operator and analysis laboratory. This collaboration is not generally seen in the helicopter industry as yet. Should SOAP or other oil analysis techniques be specified through failure analysis or maintenance philosophy for prevention of flight critical failures then this collaboration must exist.

(f) Constructors should provide design features, methods and procedures for safe and reliable extraction of oil samples. (See also 10.3.1(d))

10.4 Rotor Track and Balance

Rotor track and balance technology, as applied during the trials, offered great potential as a maintenance aid but its ability for providing direct monitoring of potentially catastrophic faults was minimal. However, it should be acknowledged that indirect benefits to safety, that cannot be quantified, are to be expected from a smoothed rotor by way of reducing pilot fatigue, airframe deterioration, increased avionics integrity etc.

10.4.1 Rotor track and balance functions were integrated into both trials helicopter types but required much effort. Only in the Super Puma trial were rotor track and balance adjustment diagnostics successfully established before completion of the trial period. It then gave identifications for main rotor irregularities and instructions for spanwise mass, blade tab and pitch link adjustments. Although provisions for rotor system monitoring were planned for the S61N, they were not implemented during the trial.

10.4.2 The supply of consistently accurate data proved difficult and required robust data integrity checks. The trial demonstrated the importance that the diagnostics software package be supplied with accurate data and the recommended adjustments be carried out by an experienced line engineer. In particular, tracker data exhibited a loss of measurement accuracy when pointing directly into sun light or where insufficient contrast between blade and background existed. Further problem sources included incorrectly fitting sensors, loose accelerometers, blade identification misunderstandings and incorrectly carried out maintenance actions.

10.4.3 It is reasoned that potentially catastrophic faults may manifest in a similar manner to adjustable (normal) faults and it is therefore possible that such a defect may be masked by subsequent maintenance actions. It is important that before making any prescribed adjustments, the maintenance engineer, by instruction, should inspect the equipment prior to any adjustment. Although rather indiscreet, this basic form of health monitoring logically offers additional safety benefit to the scheduled inspections normally performed. Trending subsequent rotor track and balance downloads either manually or by software regimes would further enhance that basic safety benefit.

10.4.4 Current rotor track and balance technology has inherent limitations in its potential for monitoring the health of rotor system dynamic and static components. Research effort is required to maximise the potential for rotor track and vibration data in providing airworthiness benefits. The adjustment diagnostics employed on the trial utilised '1R' data averaged techniques but other forms of 1R and NR non averaging analyses were investigated to see if additional diagnostic information may be extracted from larger data blocks to tackle higher frequency vibrations and to enable early defect detection. The data gathered could not satisfactorily address this but served to highlight some of the issues for future research effort.

10.5 Airframe Vibration

Airframe vibration signature analysis is a long established ground-based maintenance tool. In gathering and analysing airborne airframe vibration signatures the Super Puma trial expected to further explore the benefits for monitoring a potentially wide range of mechanical faults. Although intended to monitor both 1R and NR vibrations the possibility to monitor airframe vibration frequencies greater than 1R was precluded due to the modification of the trial system to ensure good resolution for the 1R vibration measurements for main rotor adjustment diagnostics.

10.5.1 Vibration signatures were successfully acquired and on examination supported the basis that mechanical faults have a varying effect throughout the airframe. It can be concluded that to give visibility to a range of airframe and systems faults, accelerometers should be distributed throughout the airframe.

10.5.2 Extensive research effort is required to establish relationships between measurement patterns, their fault conditions and to establish the contributions to signature variability of helicopter state and ambient condition.

10.6 Control Load Measurements

Strain gauges were attached to main rotor system static elements of the Super Puma machine (servos and support struts). By acquiring in-flight measurements of strain fluctuation, correlation between these and loads calculated or measured on prototype machines would be possible, thereby validating or modifying the safe fatigue substantiation of parts.

10.6.1 Difficulty was experienced in strain gauge installation which required specialist skills and much effort. However, once successfully attached the gauges proved reliable with valid data blocks of in-flight measurements being recorded.

10.6.2 The downloaded data proved of limited use to the operator but could have been of interest to the constructor. Although supplied to the constructor, the analysis of the results was not reported, therefore, no comment could be made on the degree of monitoring required and how this may validate or modify fatigue substantiation of parts.

10.6.3 In consideration of the difficulties of attachment of strain gauge elements particularly to rotating components, and the complexity for analysis of the down loaded data this type of monitoring technique does not appear suitable for retrospective embodiment, but on constructors initiative could be embodied into new helicopter types if desired.

10.7 Bearing Temperature Monitoring

By attaching thermocouples to the outer housings of the tail rotor drive shaft hanger bearings it was supposed that bearing distress giving an increase in temperature would be monitored.

10.7.1 The trial demonstrated that reliable data could be collected from sensors attached to the outer housing of each bearing monitored.

10.7.2 Alert levels were not defined. It is for the constructor to determine these by establishing the relationship between bearing distress and temperature effect. If it is established that monitoring temperature rise does not provide an adequate warning period then consideration should be given to siting sensors closer to the bearing raceways or developing alternative techniques such as vibration health monitoring.

10.8 Engine Health Monitoring

Monitoring the health of engines was not formally included in the trial, this technology already being well defined and understood. The trial limited its resources to the challenge of monitoring rotor and transmission system flight critical elements for which technology was less well established.

10.8.1 The trials system fitted to the S61N integrated this function and before the end of the trial correct acquisition of engine and air data parameters was demonstrated.

10.8.2 The performance of pilot initiated engine power assurance checks by the airborne system was demonstrated and validated. No limit exceedences were logged, however none were manually reported during the trial period.

10.8.3 No reason was identified that precludes engines installed in helicopters from enjoying the safety and maintenance benefits experienced by engines installed in fixed wing aircraft.

10.9 Reliability of Trials Equipment

10.9.1 *Airborne Equipment*

(a) Although both systems were, in essence, prototype or development equipment intended only for technology demonstration, the reliabilities experienced were sufficiently good that production systems with similar functions could be expected to achieve reliability levels that would realistically allow systems to be installed, used and maintained during normal revenue flying.

(b) After commissioning periods, no failures were experienced with the avionics units.

(c) The accelerometers proved to be reliable with no failures experienced during either trial.

(d) Problems experienced suggested that extra care would need to be taken for production systems to provide for,

- Rigid mounting of azimuth pickups (see also (e))
- Rigidly affixed accelerometer mounts wherever possible but if bonded particular care is required for surface preparation.
- Protected routing of cabling and connectors with due provision for avoiding oil and moisture ingress.

(e) Failures did occur to the inductive tachometer probes due to cable breaks from flexure due to high vibration. This resulted in loss of the azimuth signal required for transmission vibration analysis and unless a suitable back-up signal is provided this disables the health monitoring functions served.

(f) The total time flown by the systems during the course of the trials was insufficient to assess the Mean Time Between Failure. However it is clear that production systems will suffer unserviceabilities such that consideration should be given to Minimum Equipment List (MEL) allowances. Any allowances made should be related to system function and while a short period of loss of health monitoring function may be acceptable another function such as usage monitoring for fatigue life calculation may require the system to be despatch critical where no provision for manual recording exists.

(g) Modifications to hardware and software were required throughout the trial period highlighting the importance for tight configuration control procedures and the use of passwords on ground stations where software changes can be introduced.

10.9.2 *Ground Based Equipment*

Both trial systems employed data transfer equipment and ground station computers.

(a) The RADS-AT and Toshiba portable lap-top computers used for data retrieval and transfer demonstrated high levels of reliability. The Toshiba unit failed once due to a defective micro-chip.

(b) Reliability of the Ground station PC based computer proved good. Failures reported during the trial were limited to one floppy disc drive and transit damage.

10.10 Presentation of Health Monitoring Data

10.10.1 *Data Retrieval and Transfer*

(a) The trials confirmed the importance of quick and reliable data retrieval and, where necessary, transfer to the ground station computer to permit timely go/no-go decisions to be made consistent with flight line turnaround procedures and time scales.

(b) The advantages of a purpose built Data Transfer Unit as utilised on the S61N trial were demonstrated. Its short down-load time (2 minutes), robustness and simple to use menu-driven software proved suitable for routine use by flight line engineers.

(c) The use of a commercial portable lap top computer to transfer data from a small number of aircraft was shown to be acceptable for a limited period of time only (e.g. to support away from base operations). But, due to extended down load times resulting from aborted attempts and limited internal battery duration, this equipment cannot realistically be adopted for fleet wide use involving a large number of aircraft.

(d) The built-in displays for both trial data transfer units allowed quick access to processed data for review. However, for any future health monitoring system where processing of data is performed by the ground station, a simple transferable medium (tape or disc) would appear appropriate.

10.10.2 *Ground Station Data*

The ground station computers (GSC) employed adequately demonstrated that analysis, integration and presentation of complementary power train health monitoring data can be reliably achieved. At system definition early consideration should be given to the form and presentation of separate data inputs to the ground station. For example, SOAP results should be supplied in a form that allows the GSC database to be easily updated. For one trial the results had to be laboriously entered by hand. Complimentary techniques such as SOAP and RPD should establish formats that allow their correlation – trials results were supplied in qualitative and quantitative terms.

10.11 Data Analysis and Decision Making

10.11.1 On average, the trials helicopters flew twice daily but, due to the prototype nature of the equipment, rarely more than one download of data was achieved per helicopter per day. Any requirement for more frequent download analysis would be driven by the nature of the failure modes to be monitored. However, the lessons learnt during the trials and refinements anticipated for production systems should permit data analysis following each flight.

10.11.2 Ground station computers should be easy to use, offer simple routes to the data and give clear display of analysis results. It is important that there is no ambiguity in results and consequent maintenance actions. Clear go/no-go decisions should be possible at the 'first line' with sufficient data and form of presentation to allow deeper 'second line' analysis if required.

10.11.3 Both trial systems were operated on arbitrary sets of data threshold alerts and parametric rules for component rejection criteria. None of these resulted in component rejections during the trial.

10.11.4 Both prototype systems carried out analysis in-flight, which would potentially permit in-flight warnings to be given. The provision of in-flight warnings is dependent on the need being established. A better understanding of failure mechanisms and the inherent damage tolerance of critical parts will determine this need. Both are the subject of follow-on research. Further validation of the effectiveness of health monitoring techniques, and their reliability and false alert rates, would be required before in-flight warnings were provided. Even then, care would be required in phrasing flight manual instructions in order to minimise the possibility of a potentially hazardous emergency landing (or ditching) as a result of a false alert.

10.11.5 The trials activity could not in itself address the effectiveness of the health monitoring techniques employed but served to confirm the primary and fundamental role of the aircraft constructor in specifying and validating the techniques, setting the acceptance/rejection criteria and defining subsequent maintenance actions. Equipment suppliers, operators and constructors must all be active in the synthesis of health and usage monitoring systems.

10.11.6 It is anticipated that fleetwide embodiment of health monitoring systems will routinely provide vast amounts of downloaded data for analysis. The management of this data would become a key issue and offers specific challenges that must be addressed if this data is to be exploited to maximum effect. In particular, attention must be given to:

(a) More automation of data interpretation – Current systems apply threshold alerts and limited parametric rules but other characteristics contained within the data require to be manually considered by diagnostic experts to confirm the go/no go or better determine any consequent maintenance action. To maximise long-term benefits 'expert systems' or similar, should be established.

(b) Extraction of maximum information contained in the data – Alerts are presently set on rigid mathematical relationships. These, together with the signal averaging process, may result in abnormalities in the data not being identified. Other data analysis techniques capable of alerting to abnormal 'unexpected' data characteristics need to be established. Such supplementary techniques give some independence from the signal averaging process would be advantageous.

10.12 Operational Aspects

10.12.1 Although involving a small number of aircraft, the trials were successfully completed at operational bases sited to serve the North Sea oil industry which were remote, operationally intensive and environmentally harsh locations such as the Shetland Islands and Aberdeen in the winter. It is notable that health monitoring equipment manufacturers and diagnostic specialists were located and giving support from the opposite ends of the UK, (Southern England and Wales). Modern communications, infrastructures and regular liaison visits allowed adequate support throughout the trial.

10.12.2 The manhours required to maintain and operate a health monitoring system within an operators fleet could not be quantified from the trials programme. It was felt, however, that the additional burden of the trials on the line level engineering resources was low in relation to the normal daily workload, but was observed not to be the case for the management effort required.

10.12.3 For production health monitoring systems the maintenance and management of the system must be fully integrated into the operators maintenance and logistical procedures. Clear decision chains must exist and individual responsibilities for executive command identified. Dedicated engineering support staff would be required.

10.13 **Maintenance Benefits from Health Monitoring**

The purpose of this trial activity was to better establish the potential for safety benefits from advanced and enhanced health monitoring. In view of the foregoing it is considered that this objective has been achieved. It can be generally stated that safety and reliability are highly correlated and the potential for maintenance benefit must, therefore, be real. As with most other aspects for health monitoring implementation the prime involvement of the constructor is of importance.

11 FOLLOW-ON RESEARCH PROGRAMME

11.1 Following the completion of the post-HARP research programme a follow-on 3 year research programme was identified in 1990 to address outstanding questions. Funds totalling £1.72m have been made available by the same funding partners as before (CAA/UKOOA/DOTp/HSE) and a major part of this programme is concerned with health monitoring issues.

11.2 To further assess and establish the effectiveness of the health monitoring techniques used in the operational trials, Westland Helicopters and Eurocopter-France have been contracted to study the crack propagation in gearbox gears, webs and shafts and the effectiveness of health monitoring techniques at normal operating loads for S61N and Super Puma main rotor gearboxes respectively. For both tests, eight faults are to be 'seeded' in various components including high speed gears, shafts and epicyclic gear stages. In addition, another monitoring technique, audio monitoring and 'Stresswave' sensors are being employed to determine their performance, and oil monitoring is also being carried out. Both test programmes commenced in 1992 and should be completed by 1993/4.

11.3 Health monitoring exploits the damage tolerance inherent in a design. To promote the use of damage tolerant design techniques in helicopters, a CAA Chair in Damage Tolerance was established in 1991 at the Cranfield School of Industrial and Manufacturing Science. The terms of the chair are to research and investigate topics to 'establish design requirements, additional guidance material and safety factors for helicopter design and operation'. Various research projects are being defined and collaborative arrangements involving industry, research organisations and academia are being sought.

11.4 The feasibility of using enhanced rotor system monitoring techniques to identify potentially catastrophic failures have been studied by MJA Dynamics during 1991/2. A CAA Paper is to be published in due course to summarise the results of this work.

11.5 The prospect of developing usage monitoring techniques which would use routinely collected helicopter flight recorder data to determine fatigue life usage of critical components and the overall usage of the helicopter is being investigated. Such a usage monitoring system would have the potential safety benefit of validating the original design assumptions and would also have the commercial benefit for the operator of extending times between overhauls.

11.6 The application of expert systems/neural networks to provide more effective health monitoring data management and analysis are to be studied during the seeded-fault gearbox test programme.

11.7 This follow-on research programme is now into its second year and CAA expects to publish a review document for the seeded-fault gearbox test programme in 1994 and other research reports as and when available.

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(4) Discussion Paper on the Airworthiness of Group A Helicopters. CAA November 1989.

(5) BIHL/SHL/HSDE Final Report on CAA Operational Trial (January 1992. Ref. SHL965(1)) – CAA Paper 93004 dated February 1993.

(6) BHL/SI/WHL Operational Trial of Helicopter Health Monitoring Techniques – Precis of Final Report (10th September 1991, BHL Document No. BHL/HUM/1054A.) – CAA Paper 93003 dated February 1993.

(7) BCAR Paper G811 Health Monitoring, 24th January 1989.

SUMMARY OF THE REPORT OF THE WORKING GROUP ON HELICOPTER HEALTH MONITORING – CAA PAPER 85012, AUGUST 1985

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 be 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.

BHL AS332L SUPER PUMA OPERATIONAL TRIAL

1 MAJOR PARTICIPANTS :

1.1 Bristow Helicopters Limited (BHL)

Responsible for the following :

- Trials management
- System Integration and Installation
- Test and Operational flying
- Trials Support and Data Analysis
- Reporting to the CAA.

1.2 Smiths Industries Limited – Basingstoke (SI)

- Design and manufacture of airborne HUM Computer (0854 KEL) and Vibration Analysis system (VAS)
- Supply of Control Display Unit (CDU) and a Data Transfer Unit (DTU).

1.3 Westland Helicopters Limited (WHL)

- Analysis of gearbox vibration data
- Development of Algorithms
- Advice on instrumentation
- Use of oil debris monitor test facilities.

1.4 M.J.A. Dynamics Limited (MJAD)

- Development of rotor system diagnostics
- Advice on rotor track and balance instrumentation requirements.

2 MINOR PARTICIPANTS

2.1 **Stewart Hughes Limited (SHL)** – Supply of main rotor blade tracking system.

2.2 **Aerospatiale** – Advice on trial equipment installation. Reports on strip examination of gearboxes.

2.3 **Sensys** – Supply of 'FERROSCAN' oil debris monitoring system.

2.4 **Endevco** – Suppliers of gearbox and airframe accelerometers, advice on installation.

2.5 **Welwyn Strain Measurement** – Supply of strain gauges, advice on installation and training courses.

2.6 **Spectro Laboratories** – Oil debris analysis and Electron Microscope examination of wear particles.

2.7 **Swansea Tribology Centre** – Oil debris analysis and advice on tribology.

2.8 **Century Oils** – Oil debris analysis.

BIHL S61N OPERATIONAL TRIAL

1 MAJOR PARTICIPANTS :

1.1 British International Helicopters Limited (BIHL)

Responsible for the following:

- Trials management
- Design, manufacture, certification and installation of aircraft cable looms and equipment mountings.
- Test and operational flying
- Trial support and data collection
- Reporting to CAA

1.2 Hawker Siddeley Dynamics Engineering Limited (HSDE)

- Design and development of engine monitoring and airborne data management sub-system
- Production of airborne equipment

1.3 Stewart Hughes Limited (SHL)

- Development of gearbox and rotor vibration monitoring sub-system
- Development and provision of ground station computer and Data Retrieval Unit.
- Trial support and data analysis

2 MINOR PARTICIPANTS

2.1 **Endevco** – Supply of accelerometers and advice on installation

2.2 **Vickers-Tedeco** – Supply of 'Zapper' airborne oil debris monitoring system and chip detectors.

2.3 **Spectro Laboratories** – Spectrographic Oil Analysis programme results

2.4 **Swansea Tribology Centre** – Oil Debris analysis and advice on tribology

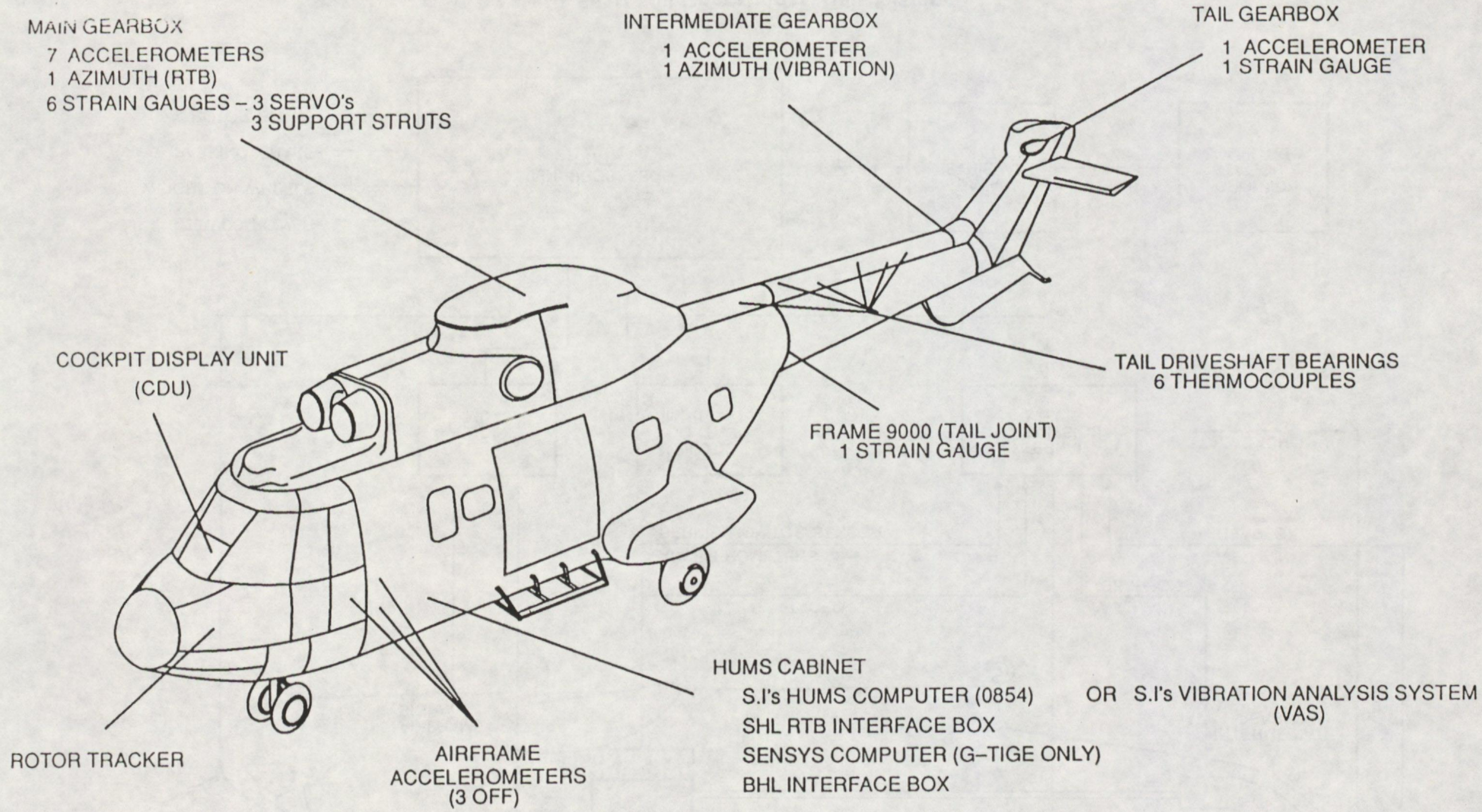


Figure 1 – BHL Super Puma Full Operational Trial System

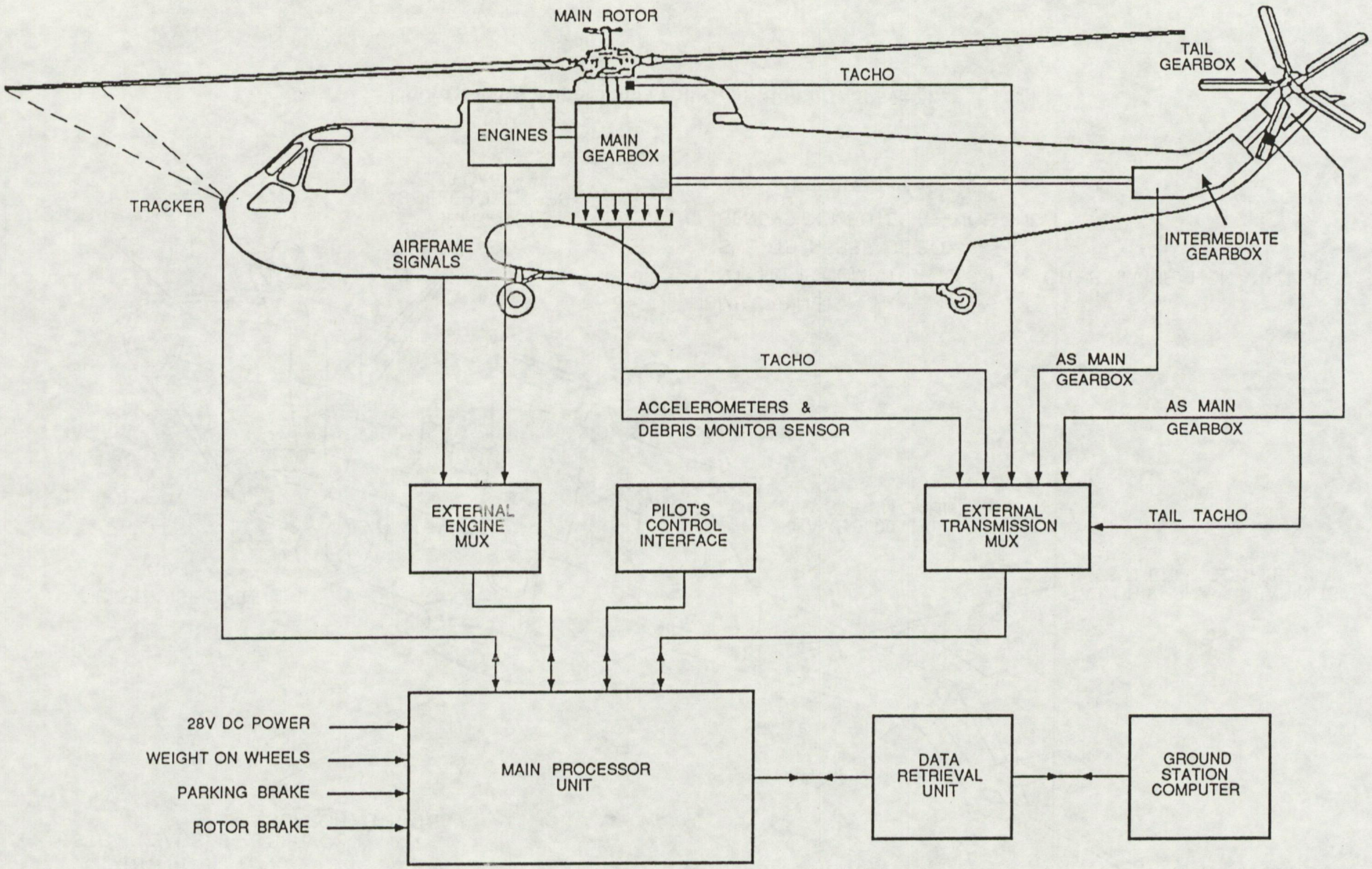


Figure 2 – BHL S61N Full Operational Trials System

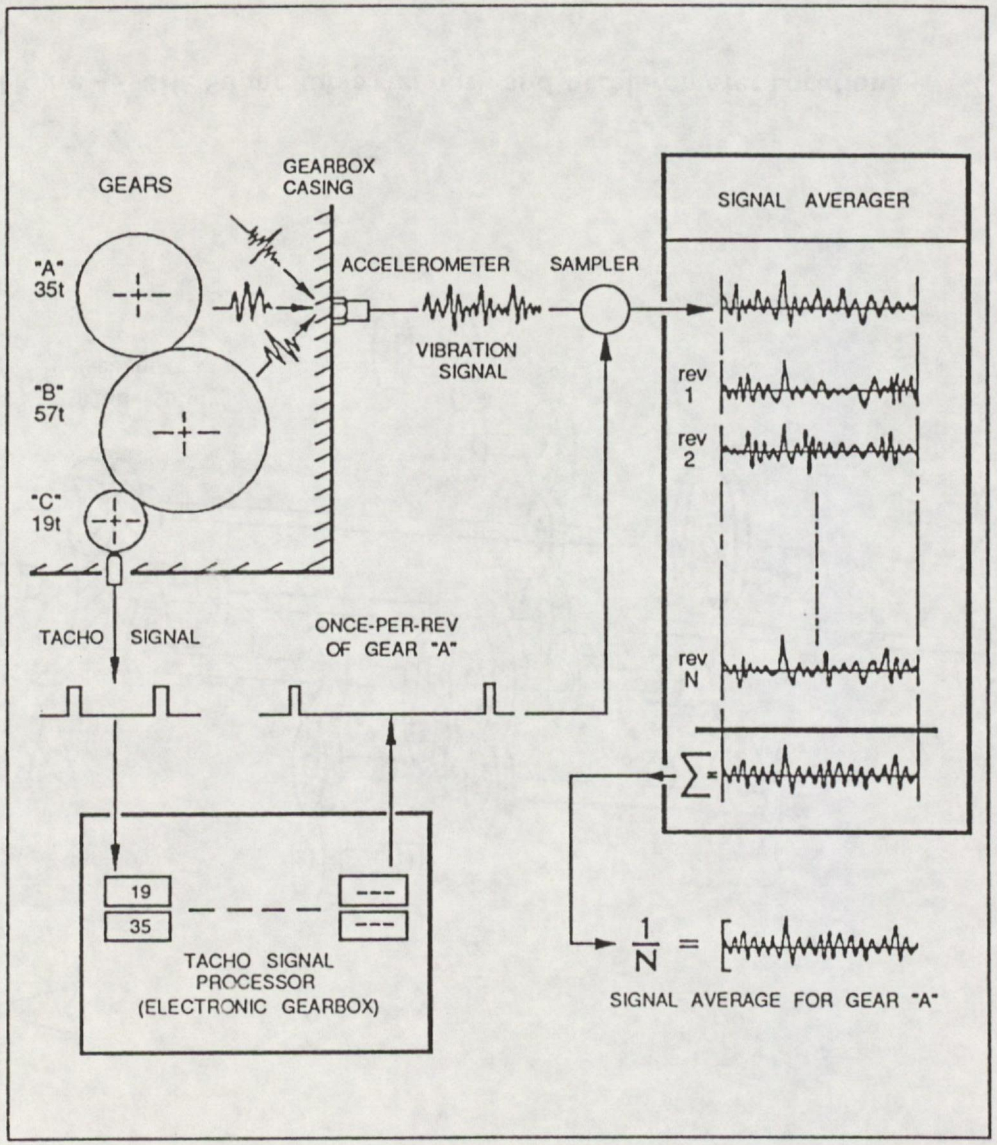


Figure 3 – Typical Gear Signature Acquisition

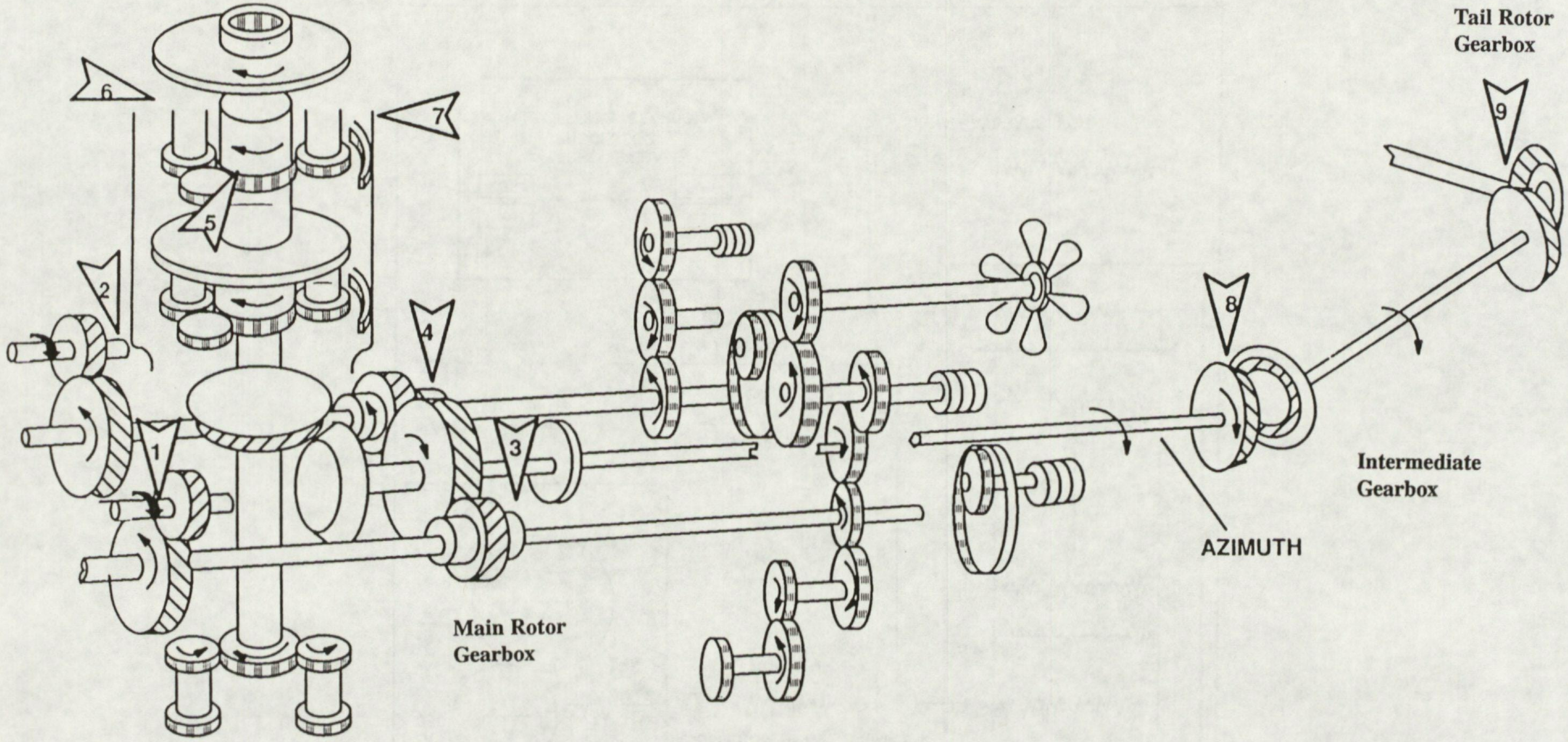


Figure 4 – BHL Super Puma Azimuth and Accelerometer Locations

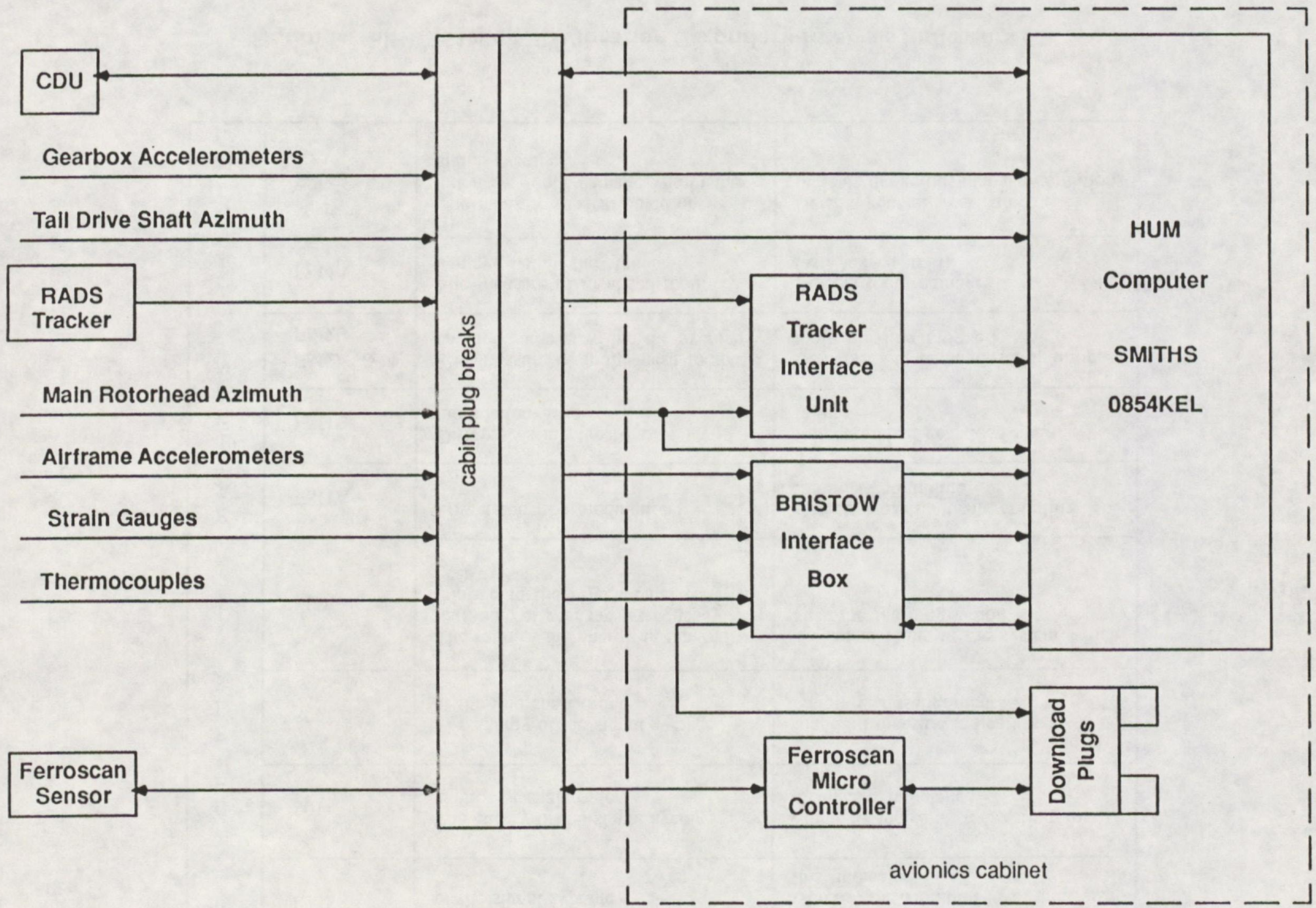


Figure 5 – BHL Super Puma Airborne System – Schematic

DIAGNOSTIC INDICATOR		CHARACTER	PURPOSE
LEVELS	RMS	The rms level or standard deviation of the signal average	All faults involving damage may increase the vibration level and raise this indicator
	S01	The energy of the signal average at the 1st shaft order	Standard indicator for testing for changes in imbalance
	S02	The energy of the signal average at the 2nd shaft order	Standard measure indicating coupling misalignment
	MFn	The ratio of the energy in the 2nd harmonic of gear mesh frequency relative to the fundamental for gear n	To detect faults in the system which alter the meshing action
PATTERN MATCHING	FM1A	Low frequency modulation	Detects misalignment, coupling failure, web failure
	FM1B	Differences in planet-pass modulation level	Detects planet gear load sharing failure
	FM2A & FM2B	The measure of multi-mesh tooth damage patterns within the average	Detects tooth damage, eg spalling, tooth bending fatigue
	FM4A	The measure of localised tooth damage within the signal	Detects tooth damage (as FM2A and B)
	FM4B	The measure of distributed or extensive tooth damage within the signal average	Detects general wear and can indicate dangerous damage conditions

Figure 6 – BIHL S61N – SHL Vibration Secondary Analysis Indicators

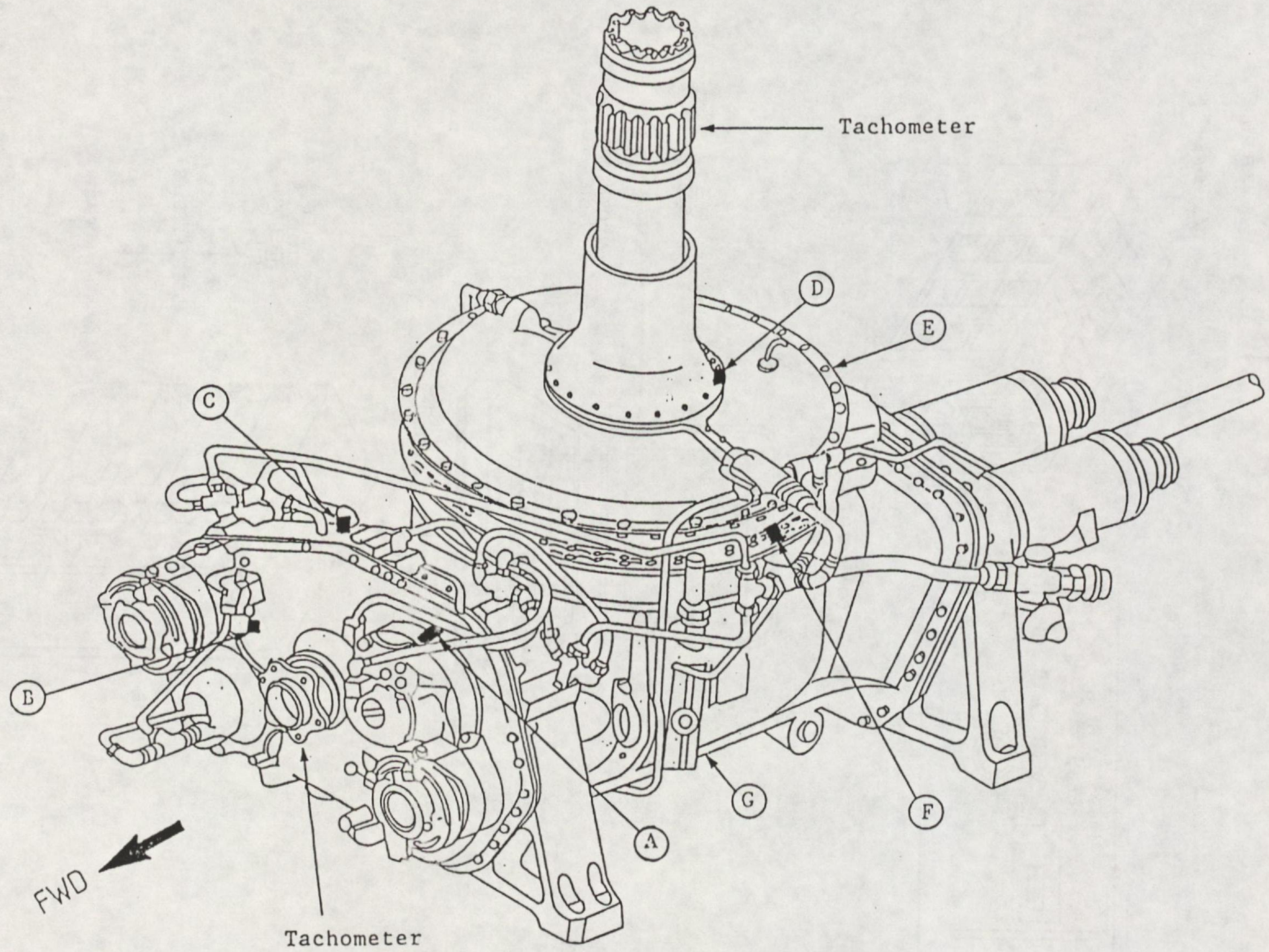


Figure 7 – BIHL S61N Main Gearbox Accelerometer Locations

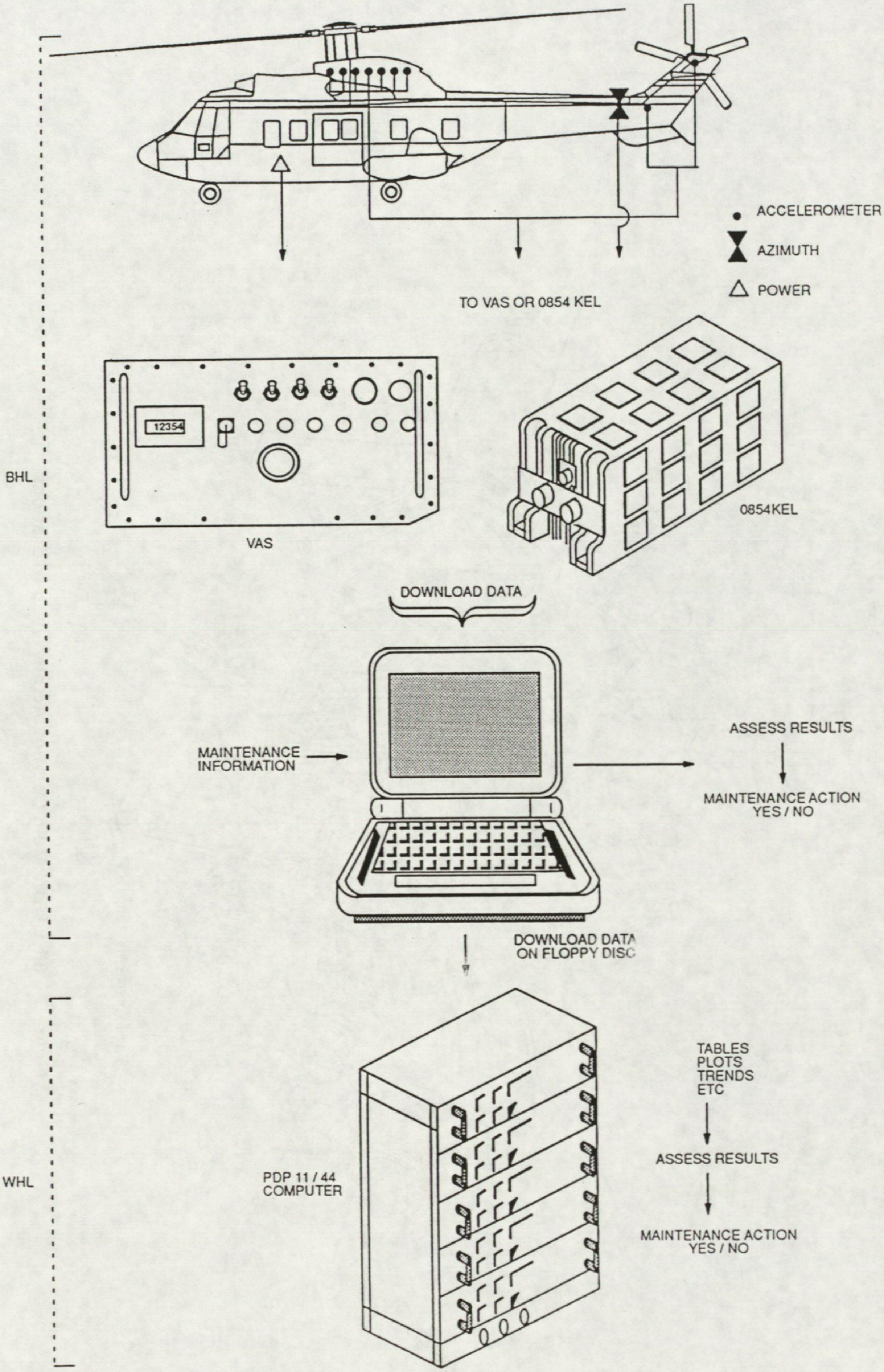
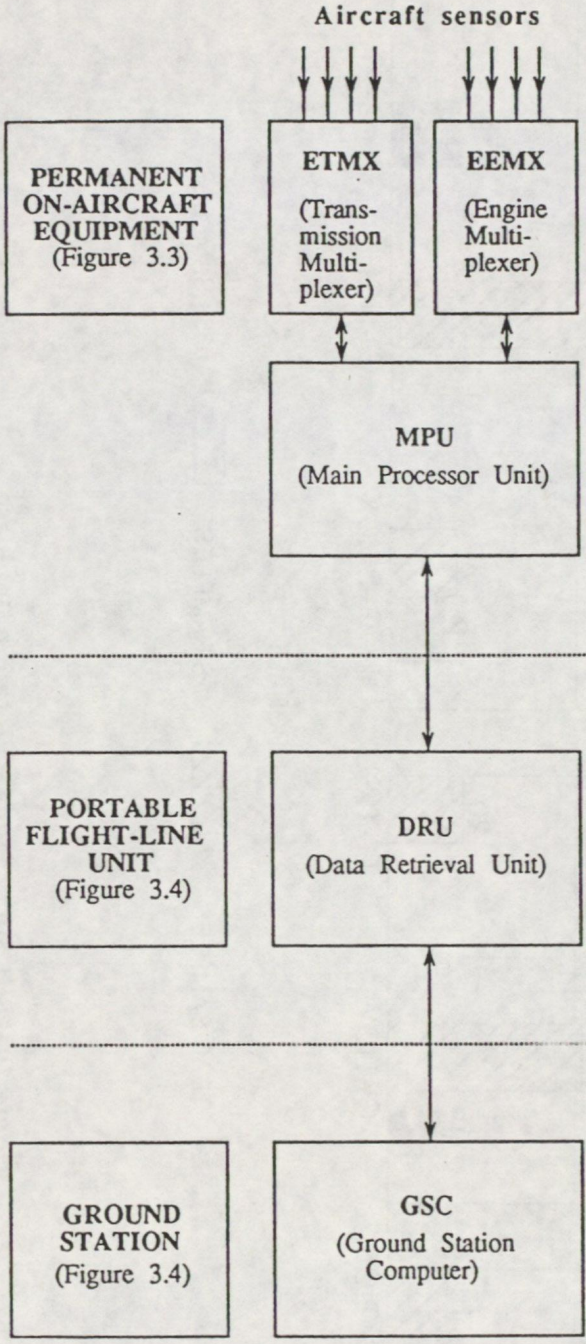


Figure 8 – BHL Super Puma – System Components

COMPONENT	FUNCTION



ETMX / EEMX:

- Multiplexing
- Signal conditioning

MPU:

- Flight regime recognition
- Data acquisition
- Data analysis (engines, transmission, rotors)
- Interpretation of results
- Storage of results
- Recording of threshold exceedances for immediate post flight warning
- MPU fully configurable from GSC

DRU:

- Immediate post-flight display of aircraft status
- Transfer of results and exceedance records from MPU to GSC
- Transfer of MPU configuration from GSC to MPU
- On-aircraft equipment testing
- Menu driven software

GSC:

- Set-up of configuration for MPU data acquisition and analysis
- 'Learning' of damage detection thresholds
- Hierarchically structured database for analysis results
- Mimic displays for component data selection and failure warning indications
- Data interpretation and trending
- Menu driven software

Figure 9 – BIHL S61N – System Components and Functions

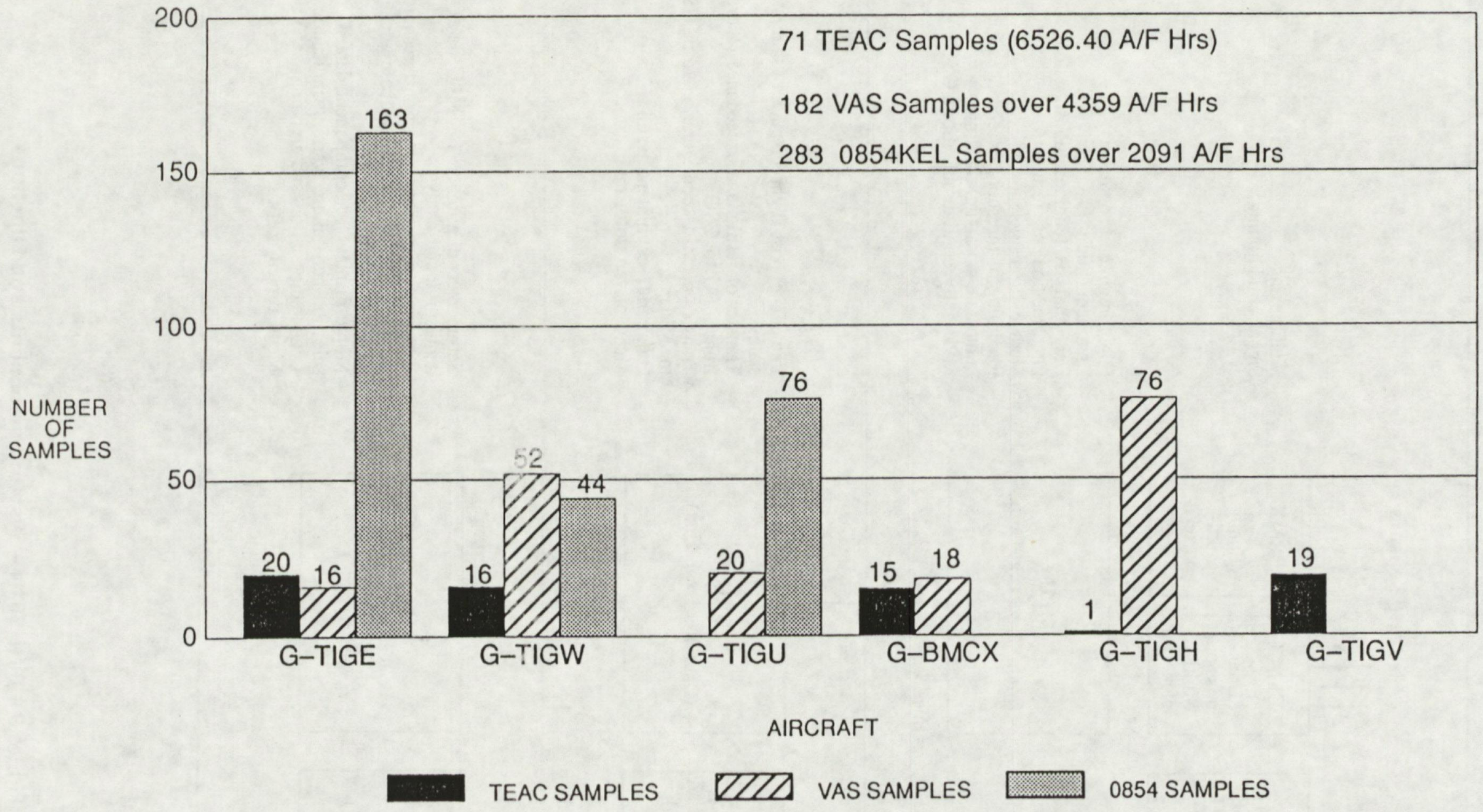


Figure 10 – BHL Super Puma – Vibration Database

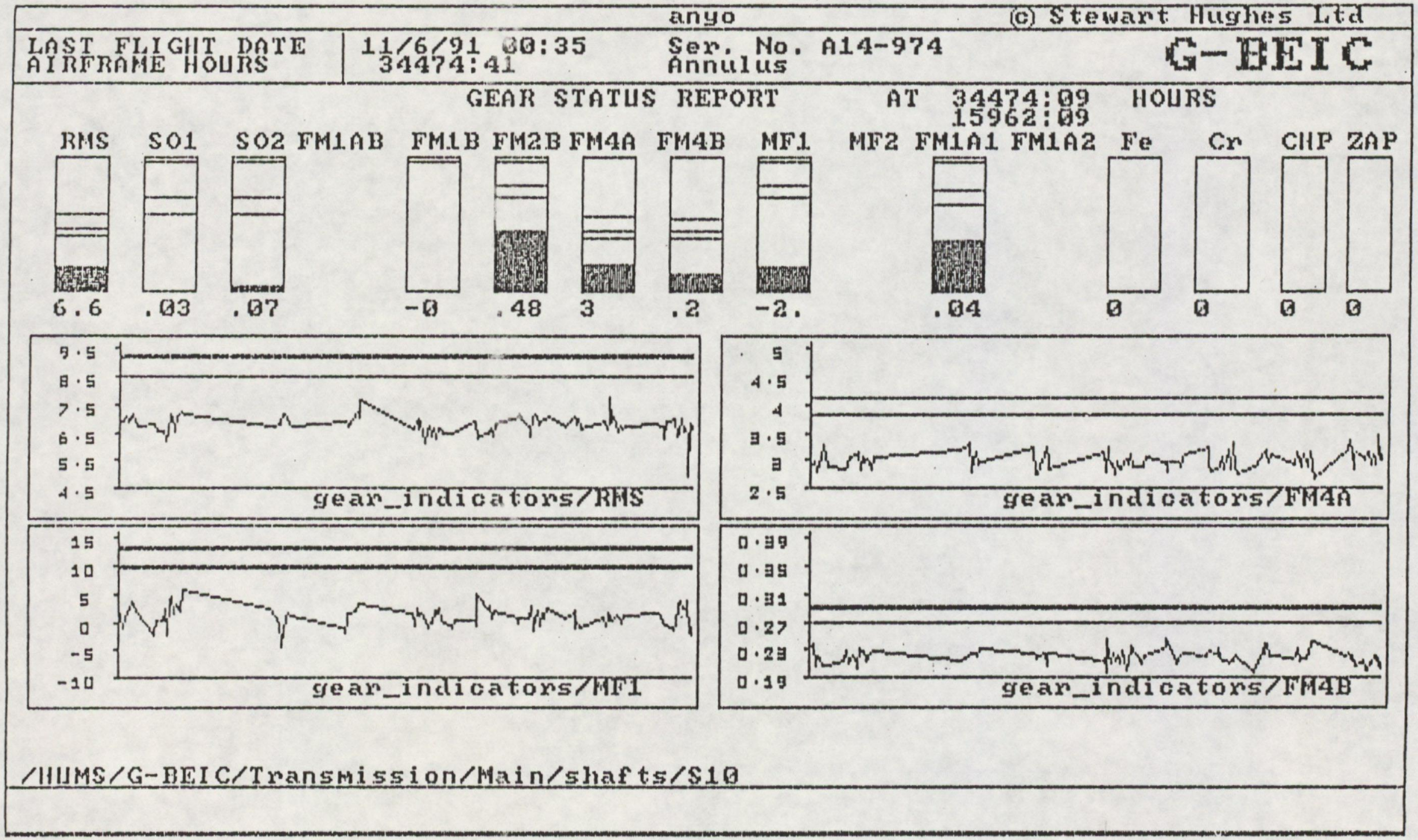


Figure 11 – BIHL/SHL Gear Status Report Format