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HELICOPTER HEALTH MONITORING

British International Helicopters Ltd – Operational Trial of Sikorsky S61N Health and Usage Monitoring System Demonstrator

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This Paper presents the British International Helicopters Limited Final Report dated January 1992 on the S61N Operational Trial of a Health and Usage Monitoring System. This was one of two operational trials which were carried out between 1987 and 1991 as part of a helicopter safety research programme which were funded by CAA, the UK Offshore Operators Association and the UK Departments of Transport and Energy (now HSE).

The views expressed in this document are those of British International Helicopters Ltd. An overview document which reviews both operational trials has been produced by CAA (CAA Paper 93002).

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GLOSSARY OF TERMS

ADU	Air Data Unit
ABT	Auto Blade Tracker
Alt or PO	Pressure Altitude
A/C	Aircraft (includes helicopter)
ADC	Analogue to Digital Converter
ATR	Air Transport Racking
AV	Analogue Verification
BIHL	British International Helicopters Limited
CAA	Civil Aviation Authority
DMC	Data Management Card
DRU	Data Retrieval Unit
DTI	Department of Trade and Industry
EEMX	External Engine Multiplexer
EMI	Electro-magnetic Interference
ETMX	External Transmission Multiplexer
FFT	Fast Fourier Transform
FMECA	Failure Modes, Effects and Criticality Analysis
GCA	Ground Crew Access
GSC	Ground Station Computer
HSDE	Hawker Siddeley Dynamics Engineering
HUMS	Health and Usage Monitoring System/s
IAS	Indicated Airspeed
LCF	Low Cycle Fatigue
LEL	Limit Exceedance Logging
MUX	Multiplexer
MPU	Main Processing Unit
MTBF	Mean Time Between Failures
Nf	Engine power (free) turbine rotational speed
Ng	Engine gas generator (compressor) rotational speed
NO	Normal Operation
Nr	Helicopter Rotor speed
NVM	Non-Volatile Memory
OAT	Outside Air Temperature
PAC	Engine Power Assurance Check
PCI	Pilot's Control Interface
PDF	Probability Density Function
PDSP	Programmable Digital Signal Processor
PQI	Particle Quantity Index
PUST	Power Up Self Test
RGCA	Restricted Ground Crew Access
RPD	Rotary Particle Depositer
RT&B	Rotor Track and Balance
S61	Sikorsky S61 Helicopter
SHL	Stewart Hughes Limited
SOAP	Spectrographic Oil Analysis Programme
Spectro	Spectro Oil Analysis Company
T2 or AIT	Engine Air Intake Temperature
T5 or PTIT	Engine Power Turbine Inlet Temperature
TPC	Transputer Processor Card
TQ	Engine Output Torque
UKOOA	United Kingdom Offshore Operators Association
VDAC	Vibration Data Acquisition Card

1.0 INTRODUCTION, TRIAL OVERVIEW AND CONCLUSIONS

1.1 Introduction

The June 1984 report of the Helicopter Airworthiness Review Panel (HARP) recommended that the UK Civil Aviation Authority (CAA) should set up a working party to investigate new or improved condition monitoring devices and systems.

The working party on Helicopter Health Monitoring published CAA paper 85012 in August 1985, making the following recommendation: "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".

Following this report, the CAA, the British Government and the United Kingdom Offshore Operators Association (UKOOA) made available funds for research and further promotion of a better understanding of Helicopter Health Monitoring. Additional funding was separately made available by the DTI for the development of the trials equipment.

British International Helicopters Limited (BIHL) agreed to establish and manage a Health and Usage Monitoring Systems (HUMS) trial on two Sikorsky S61N helicopters performing their normal operational role in the North Sea. It was originally planned that these aircraft would be based at Aberdeen. The CAA placed a contract with BIHL in March 1988.

The trial was intended to demonstrate technology for in-flight data acquisition and analysis to provide health and usage monitoring of a helicopter power train, including engines, the transmission system and rotors.

It was proposed to incorporate the following functions in an airborne HUM system; on-line vibration monitoring of the main, intermediate and tail gearboxes; oil debris monitoring; engine health and usage monitoring; main rotor track and balance and tail rotor balance. Off-line gearbox oil and debris monitoring was also to be integral part of the trial.

The trial was intended to include the demonstration of ground based equipment to interface with the airborne system and enable the storage and display of all monitoring information. This enabled the system engineering and operational aspects of HUMS to be addressed.

Reference 1 defined the objectives of the trial, these are repeated below:

1 To provide a research tool with which to investigate the suitability, reliability and capability of a Health Monitoring System for vibration and on-line

ferrous oil debris monitoring of the gearboxes, main rotor track and balance, engine health monitoring and an off-line analysis of the oil and debris from plugs/filters.

2 To expand the overall knowledge in the use of Health Monitoring Systems in Helicopters to supplement data and experience gathered from other programmes.

3 To prove the reliability of the Health Monitoring System when operating in a typical offshore oil support environment.

4 To determine effective methods of integrating Health Monitoring Techniques into a commercial operator's Maintenance Management System and Procedures.

5 To investigate what airworthiness credit could be given to this type of installation.

Section 2 of the report describes the monitoring technology incorporated in the trial. Section 3 introduces the HUMS and describes the system hardware, Section 4 gives a functional description of the system. Section 5 describes the trial experiences, Section 6 considers the use of HUMS data and Section 7 presents a general discussion.

Although the trial was formally completed in August 1991, the prototype HUMS continued to produce data until it was removed for a production FDR/HUMS fit at the beginning of December 1991. This additional data has been included in the report. The main rotor gearbox was removed at this time and a strip report on the condition of the gearbox will be published separately.

1.2 Principal companies

1.2.1 *British International Helicopters Limited*

British International Helicopters Limited (BIHL) operates a mixed fleet of helicopters from four bases in the UK. The bulk of Company work is in support of the North Sea oil industry, flying from Sumburgh in the Shetland Isles, Aberdeen, and Beccles, near Great Yarmouth. Scheduled passenger services to the Isles of Scilly are operated from Penzance and Newquay.

The BIHL fleet consists of 16 Sikorsky S61Ns operating from Beccles, Aberdeen and Sumburgh, 6 AS332L Super Pumas based at Aberdeen, and 4 Sikorsky S76s split between Beccles and Aberdeen.

The largest base is at Aberdeen, where comprehensive engineering support facilities are based. Major structural work on Royal Air Force Dominie aircraft is undertaken at Aberdeen. The Company is also engaged in a major refurbishment programme on Lynx shipborne helicopters of the Royal Netherlands Navy.

The backbone of the Company is North Sea oil industry support work. BIHL holds a long term contract with Shell UK Exploration and Production, for the support of installations in the East Shetland Basin of the Northern Sector of the North Sea.

1.2.2 *Hawker Siddeley Dynamics Engineering Limited*

Hawker Siddeley Dynamics Engineering Limited (HSDEL) specialises in the design, development, manufacture and support of control and monitoring systems for harsh environments. The company supplies both military and industrial grade equipment for aero, marine and land based applications.

HSDELs aviation experience dates from 1957 when the company designed the worlds first full authority gas turbine fuel control system. Several thousand of these systems, controlling the Rolls-Royce Gnome engine, have been delivered to 19 operators.

More recently, the company has designed a range of Full Authority Digital Engine Controls (FADEC) for the helicopter market, a recent example being the FADEC for the Texron Lycoming T55 engine which powers the latest version of the Boeing Chinook, the MH-47E.

The company employs approximately 450 people, of these some 250 are in the manufacturing plant and approximately 90 are engineers. The engineering department includes the specialist skills needed to manufacture certified flight standard equipment: the overall system design, the design of flight critical software, the design of aerospace quality hardware and the qualification of the systems to meet both European and American quality standards.

The company holds quality approval from the UK Ministry of Defence and the Civil Aviation Authority.

1.2.3 *Stewart Hughes Limited*

Stewart Hughes was formed in 1980 by a small team of mechanical and systems engineers from the Machinery Health Monitoring Group at the Institute of Sound and Vibration Research (ISVR), Southampton. This team has greatly expanded to cover a much wider range of interdisciplinary engineering activity, and now includes specialists in software, mechanical, instrumentation and electronic engineering.

Stewart Hughes has pioneered the use of advanced vibration based diagnostics capable of reliably detecting fatigue related damage in transmission systems. The company specialises in developing both hardware and software for machinery management technology over a wide range of applications which include: helicopters, aero engines, computer integrated manufacturing, process plant, mining and marine engineering.

The company has expertise in the specific areas of helicopter rotor dynamics and transmission systems, diagnostic monitoring systems, artificial intelligence, signal processing, electrostatic gas turbine intake and exhaust debris monitoring systems.

In partnership with Scientific Atlanta, SHL developed the RADS-AT/AVA helicopter rotor track and balance system which has been purchased in large numbers by the US Army.

1.3 Trial organisation

The organisational structure of the trial is shown in Figure 1.1. British International Helicopters Limited were appointed project managers for the trial and were responsible for provision of the aircraft and the day to day control of the project. BIHL carried out the tasks of design, certification and installation of the aircraft cable looms and equipment.

HSDE and SHL were jointly responsible for the development of the HUM 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 the original plan was to base the trial at Aberdeen, the trial was actually conducted using two Sikorsky S61N helicopters operated by BIHL from Sumburgh, on the southern tip of the Shetland Isles, 190 miles north of Aberdeen. The aircraft carried out normal BIHL operations, without special tasking considerations being made for the HUMS installation, the intent being to monitor an aircraft in representative service.

The distance between HSDE and SHL, based in the south of England, and the location of the trial in the Shetland Isles considerably increased the difficulties of these companies in supporting the trial systems. However the exercise proved the feasibility of operating HUMS in a remote location.

1.4 Monitoring techniques

This section briefly summarises the monitoring techniques which were planned to be incorporated in the HUMS trial

(Reference 1). The monitoring techniques are described in more detail in Section 2.0.

Vibration monitoring

Gears and shafts were to be monitored using the Stewart Hughes Gear Analysis technology. This incorporated two basic processes: Primary Analysis - the production of component vibration signatures using synchronous averaging; Secondary Analysis - the computation of indicators related to the health of the transmission (energy indicators and Figure of Merit (FM) numbers FM1 to FM5).

It was intended to carry out vibration monitoring of rolling element bearings in the helicopter gearboxes using Stewart Hughes Bearing Analysis techniques.

On-line oil debris monitoring

The airborne system was to provide a capability for integration of outputs from standard chip detectors and a Tedeco zapper fuzz burner chip detector with other monitoring data.

Main rotor track and balance and tail rotor balance

The system was intended to continuously monitor main and tail rotor balance, with a capability to acquire main rotor track data from an optical sensor when a requirement was indicated from the balance data.

Engine Monitoring

An engine health and usage monitoring package was to monitor the following functions: power performance, low cycle fatigue, limit exceedances and general usage functions.

Off-line oil/debris analysis

Spectrometric oil analysis (SOAP) was carried out by Spectro Laboratories, and debris analysis by Swansea Tribology Centre using their Rotary Particle Depositor (RPD) and Particle Quantifier (PQ).

1.5 System overview

1.5.1 *Airborne system*

The S61N trial airborne system consisted of 3 processing units (a main processing unit plus engine and transmission signal conditioning units), a pilot interface, and the system sensors.

The system was intended to survey all power train gears/shafts in the main, intermediate and tail gearboxes, and perform both main and tail rotor balance in a continuous cycle when in cruise flight. All vibration data analysis was performed in flight and the results compared against a set of thresholds for each monitored component. This data was used to give an immediate indication of transmission health when the aircraft landed. The system also provided engine monitoring functions, recording engine exceedances, performance and usage data. The airborne system was configurable from the ground based equipment, giving this HUMS a good degree of flexibility. The pilot interface allowed the pilot to request functions such as power assurance checks and rotor track and balance which require special flight conditions.

1.5.2 *Ground based system*

The ground based components of the system were the Data Retrieval Unit, (DRU) and the Ground Station Computer (GSC).

The DRU was a portable battery powered unit, providing a direct interface between the HUMS and the aircraft support crew. The power train component health status was available from the DRU at the aircraft immediately the data was transferred from the airborne system. The DRU could be used to download data from different aircraft types and allowed the HUMS to function whilst the aircraft was away from it's base. The DRU performed all data transfer between the airborne system and the ground station.

The GSC stored the data from the airborne system and displayed this in a variety of graphic and text based formats. Provision was made within the GSC for manual input of the oil analysis data. The GSC also provided facilities for configuring the analyses performed by the airborne system. The GSC could accommodate different aircraft types and could be reconfigured for any new types.

1.6 Conclusions

The conclusions derived from the trial experience are described below, grouped under different headings. Where appropriate, reference is made to sections of the main body of the report which provide supporting information.

1.6.1 *General*

In respect of proving the feasibility of a HUM system to provide on-aircraft real-time monitoring of the power train, it is considered that the trial system met this aim. By the end of the trial the prototype HUM system was producing consistent and reliable data of good quality.

The trial has demonstrated that HUMS can successfully be retrofitted to an existing aircraft. All of the monitoring techniques demonstrated were readily adapted to the S61N. The trial indicated that the concept of HUMS could be applied to different aircraft types without difficulty.

The trial experience indicated that HUMS technology could make a worthwhile contribution to improving safety by:

(a) Providing a source of information on installed component health not previously available (eg vibration analysis).

(b) Implementing techniques in a manner such that it is possible to give an immediate after flight go/no go indication.

1.6.2 *The trials HUM system*

(a) The modularity of the airborne system and its ability to be configured from the ground station proved its worth in that it enabled several modifications to be introduced during the trial. However, the importance of tight configuration control was recognised. This was provided by use of passwords in the groundstation and automatic logging of password uses and configuration changes. (Section 4.2.2.1)

(b) During the commissioning phase some development problems with the system were encountered. In the six month (678 flight hours) post-commissioning phase, however, the trial system airborne and flight line data collection/processing units were demonstrated to have good reliability despite operating in a harsh environment, with no failures occurring. (Sections 5.2 and 5.3)

(c) Occasional problems were encountered with the method of attachment of the accelerometers to the gearbox casings. Accelerometers were bonded to the casings and a few cases of disbonding occurred. As a result of the trial experience it is recommended that accelerometers are bolted to the gearbox casing (Sections 5.2.1 and 5.2.4). Some problems also occurred with the external accelerometer and tachometer wiring, in particular the connector from the main gearbox through the transmission deck, this being vulnerable to damage. Attention must be given to these areas to ensure high overall system reliability. (Sections 5.2.2 to 5.2.4)

(d) In both of the cases quoted in item (c) failures were detected by built-in test equipment. The system stopped producing data from the affected accelerometers and did not generate any spurious monitoring data.

1.6.3 *Health monitoring techniques*

(a) The trial pioneered the development of new technology in the form of an aircraft system performing in-flight monitoring of the transmission system using advanced vibration based techniques. The system included features not previously seen in on-board vibration monitoring equipment in so much that it continuously sequenced analyses through the gearboxes, performed all the required data processing, and had automatic analysis scheduling using aircraft regime recognition.

(b) Development of the transmission vibration monitoring technology continued until quite late in the trial. Some variability seen in early data acquired under all flight conditions showed the importance of acquiring and analysing data in a consistent flight regime. Flight regime recognition for correct scheduling of analyses was implemented once the engine and air data was available. After completion of the commissioning phase the HUMS vibration analysis function was demonstrated to produce consistent good quality transmission system monitoring data. (Section 5.5.2)

(c) The gear and shaft vibration analysis techniques were successfully implemented, with the system computing transmission health indicators up to FM4. Unfortunately owing to resourcing problems within SHL the FM5 indicator, targeted at early detection of localised tooth damage in epicyclic gears, was not implemented. FM5 is still considered to be a useful addition to the indicator suite and it is hoped that it will be fully developed and implemented at some time in the future. (Section 7.4).

(d) Owing to a lack of time and resources, although the software for rolling element bearing vibration analysis was written, the techniques were not incorporated into the airborne HUMS. For oil washed bearings inside gearboxes there is an overlap in fault detection capability between on-line oil debris monitoring and vibration monitoring. However, it is believed that bearing vibration analysis can make a useful addition to the currently available transmission health monitoring techniques. There are no technical reasons why bearing analysis cannot be integrated into a HUMS, this being a generally simpler process than the gear and shaft analysis. (Section 7.4).

(e) The gear and shaft vibration monitoring function analysed the main drive train components in the main, intermediate and tail gearboxes in a round-robin schedule. Analysis of post-commissioning data showed that over 3 analyses/flight hour were carried out on the medium and low speed components, and twice that number on the high speed components. At the end of a flight the last 5 sets of results were downloaded to the flight line DRU, together with any exceedances. The multiple results allow the identification of any trends occurring within a flight and enhance confidence by preventing the taking of decisions based on a single data point. (Section 4.1.2.1, 4.2.1.1)

(f) After completion of the commissioning phase, transmission vibration analysis results were produced continuously over a period of six months and 678 flying hours before the system was withdrawn from service (Section 5.1). Downloads from the airborne HUMS were taken on average once a day (at the end of flying), and an average of approximately 650 data points were stored in the GSC for each monitored component. (Section 5.5.2)

(g) Engine monitoring and air data gathering was achieved at a relatively late stage of the trial, however the correct acquisition of engine and air data parameters was demonstrated. (Section 5.6)

(h) The performance of pilot initiated engine power assurance checks by the HUMS was demonstrated and validated. No limit exceedance data was logged, however exceedances are in practice rare events. The HUMS was demonstrated to correctly log engine, transmission and airframe usage data and there were only small deviations between manually and automatically logged usage data. (Section 5.6)

(i) Rotor track and balance functions were integrated into the airborne system but, owing to delays caused by difficulties with certification of the tracker installation and development problems, the functions were not able to be demonstrated before completion of the trial. However, these functions have been incorporated in the production HUM system, with improvements made in the implementation based on experience gained from the trial. The first production system was operational on an S61N before the trials system was withdrawn from service. (Section 7.4)

(j) On-line oil debris monitoring by standard chip detectors and a Tedeco zapper fuzz burner chip detector had been satisfactorily demonstrated by the end of the trial. Zero 'zap' counts were correctly logged by the system over a period of 350 flying hours, with inspections confirming that there was no dirt or debris on the chip detector. Delays in the introduction of the zapper function were caused by certification difficulties and by modifications to the zapper control unit which were required to prevent spurious fuzz burn discharge counts. (Section 5.7.1)

(k) The trial demonstrated that the two off-line oil/debris analysis techniques employed, spectrometric oil analysis (SOAP) and debris analysis, can give corroborating evidence of damage development. The techniques were shown to be complimentary, being sensitive to different types and sizes of debris. (Section 5.7.2)

(l) Both off-line oil/debris analysis techniques are trend indicators and much of their value lies in the establishment and upkeep of a reference database. The trial experience indicates that both techniques can give clear response to damage development, with significant changes in trends. (Section 5.7.2)

(m) The trial confirmed general experience that SOAP can be cost effective in terms of the safety benefits obtained. SOAP produces consistent results with a quick turn round, and can provide detection of defects at an early stage. The collection of samples is usually a simple and quick operation and management of a SOAP does not present any special problems, consisting of monitoring sample data collection and results (Section 5.7).

1.6.4 *Operational aspects*

(a) Line level engineering support for the HUMS trial equipment had to take second priority to engineering requirements for revenue flying, the HUMS not being an MEL item and therefore despatch critical. However, it was felt that the additional burden of the HUMS trial on the line level engineering resources was very small in relation to the normal daily workload. The trial provided some useful evidence to confirm the operational acceptability of HUM systems (Section 5.4.4).

(b) Although for a large percentage of the time only one trial aircraft needed to be supported, the fact that the trial was successfully completed in a remote, operationally intensive and environmentally harsh location such as the Shetland Isles provided further evidence on the feasibility of implementing HUM systems.

(c) The data retrieval unit, with its simple to use menu-driven software, has demonstrated itself to be suitable for use by engineers on the flight line, allowing data to be quickly downloaded during an aircraft turn around. The download took less than 2 minutes, required only aircraft battery power, and was easily integrated into the flight line turn around procedures (Section 5.4.1).

(d) The combination of in-flight analysis of data carried out by the airborne system and a portable data retrieval unit with built-in display allowed quick access to a result summary without the need for a ground station.

(e) In terms of the techniques applied, the trial demonstrated that the HUMS had a capability to provide monitoring coverage during short term operations away from an aircraft's normal base. The ability to store multiple data downloads in the data retrieval unit and subsequently retrieve these prevents the loss of trend/usage data. Provided sample bottles travel with an aircraft SOAP can also be continued away from base, with the analysis results being sent from the laboratory back to the main base. (Section 7.2.4)

(f) The HUMS ground station successfully demonstrated the integration of complimentary power train condition information from a number of different sources such as performance, vibration, chip detectors, SOAP and oil debris analysis. (Section 5.4.2)

(g) With its pictorial presentation of monitored components, simple routes to the data, and clear display of analysis results, the GSC was shown to be easy to use for routine data checking. The data on the ground station computer was presented in a form which could be readily utilised by a line level licenced engineer, with a clear indication of any monitoring threshold exceedances. Training courses will need to be run for engineers using HUMS on the vibration analysis techniques and the application of acceptance/rejection criteria based the HUM vibration health indicators (Sections 6.1 and 6.2).

1.6.5 *Looking ahead*

(a) Although the trial demonstrated the feasibility of retrofitting HUMS to an existing aircraft, there are benefits from building-in HUM facilities at the aircraft design stage to allow it to be fully integrated with aircraft systems and sensors. This will offer the maximum system capabilities at the lowest cost. For example, sensor positioning can be optimised, data transmission can be integrated (whether wiring harnesses or data buses), flight data requirements can be integrated with other systems, and HUMS functions can be integrated in a wider aircraft management system.

(b) The concept of HUMS has been pioneered in the UK with the full support of the CAA. However, it is important that aircraft constructors outside the UK become fully involved in HUMS. This must include the specification of monitoring techniques, the validation of these, and the setting of component acceptance/rejection criteria for aircraft operators.

(c) Clear instructions must be provided for the assessment of HUMS data in terms of actions which must be taken following HUM system indications. The drawing up of rejection criteria should involve the constructor to enable the establishment of universally agreed component rejection criteria (ie common for all operators).

(d) The instructions need to be evolved and refined as experience is gained from: (a) production HUM systems gathering 'normal' data from large numbers of aircraft of different types; (b) an expanding knowledge of the response of HUM techniques to damage conditions from seeded fault tests and naturally occurring arisings; and (c) constructors activities such as FMECA and the interpretation of these.

(e) For power by the hour operations, the accumulation of experience on vibration and oil analysis techniques would be considerably enhanced if, during overhauls and repairs, constructors provided gearbox strip reports which could be correlated with HUMS data.

(f) BIHL intends to continue with SOAP on the S61N main gearbox as an integral part of routine servicing, with debris analysis using the Swansea Particle Quantifier in a supporting role to provide corroborating evidence when there are indications of possible damage development.

(g) To maximise the benefits of SOAP, constructors should be involved in structured programmes with operators and specialists to evaluate SOAP data and tailor its use for different operational situations (for example gearbox modification states, oil types, and aircraft usage).

(h) At present rotor track and balance data is primarily used for maintenance purposes. However, there is growing evidence that this data can be used to detect some rotor head faults such as deterioration in lead-lag damper performance, degradation of elastomeric bearings and excessive play in control linkages. R&D effort is required to maximise the potential of rotor track and vibration data to provide airworthiness benefits.

(i) The in-flight processing of data by the HUMS offers the potential for providing in-flight warnings. The provision of such warnings must be dependent on further validation of the technology, in particular achievable false alarm rates.

(j) The recording of usage, engine performance and torque/temperature exceedance data by HUMS can be more comprehensive and accurate than manually gathered equivalents. Provided the constructor is involved, this should enable a continuation of the trend away from component life based solely on achieved running hours towards life based more on usage criteria, thus offering the potential for reduced maintenance costs.

(k) It is believed that, when substantiated, HUMS will offer many operational benefits including maintenance credits such as extension of times between overhauls. The constructor must be involved in the substantiation process if these benefits are to be realised. A precedent has been set by, in particular, civil fixed-wing operators of large turbine engines where overhaul lives have been extended to many times that originally granted by certifying authorities.

(l) The CAA trial has led to significant advances in helicopter HUM technology, culminating in the widespread installation of production HUM systems. A number of improvements have been incorporated in the production HUMS, several of these are the direct result of experience gained in the trial.

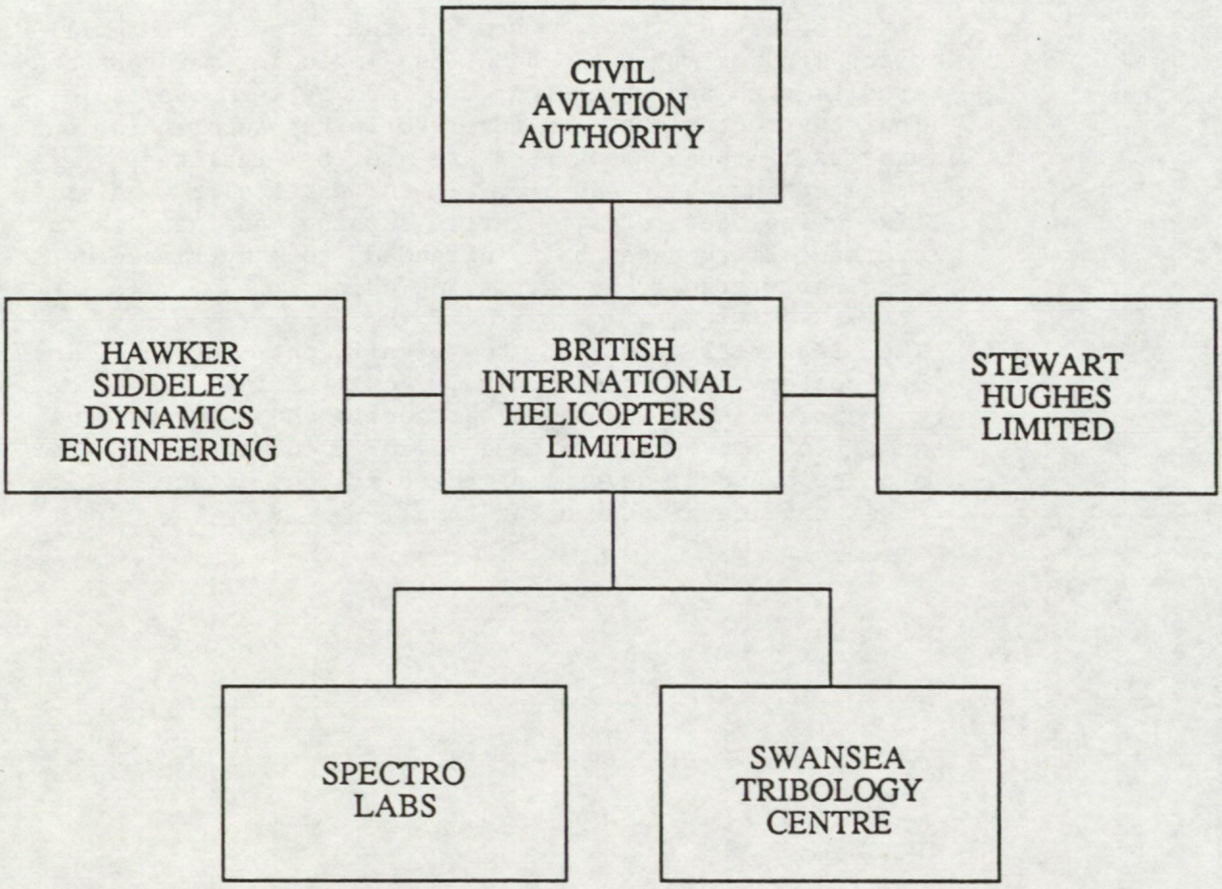


FIGURE 1.1 : Trial structure

2.0 MONITORING SYSTEM TECHNOLOGY

2.1 Transmission vibration monitoring technology

This section describes the vibration analysis technology applied in the HUMS for health monitoring of the helicopter transmission system.

2.1.1 *Failure mechanisms*

The basic rotating elements of a transmission system are gears, bearings, shafts and couplings. Each of these elements can have a range of different failure modes. Gear failure modes will be taken as an example to illustrate the requirements for vibration monitoring.

From a health monitoring point of view, gear failure modes can be divided in three broad classes:

(a) Tooth bending fatigue - fatigue cracks initiate at a tooth root and either progress under the tooth, resulting in tooth loss, or into the gear web, resulting in complete fracture of the gear.

(b) Loss of gear support - this can be the result of fatigue related structural failure of the gear hub/web, shaft or bearing.

(c) Wear - gear tooth surface damage can be caused by contact fatigue (pitting) or by lubrication related problems (scuffing). Large scale pitting can initiate a fatigue crack, leading to a tooth bending fatigue failure.

2.1.2 *Health monitoring techniques*

Several different failure mechanisms have been described, effective monitoring of these can be provided by two complementary techniques: oil debris monitoring and vibration monitoring. The techniques are complementary in that they can provide monitoring coverage for different types of damage. Only the latter is considered here, the following points illustrate some of the requirements for vibration monitoring:

- Fatigue crack development may produce no debris, vibration monitoring is the only detection technique in these circumstances.

- Oil debris monitoring can only be used for oil washed components, it's success relies on the transport of debris from the damaged component to the detector and it's capture by the detector.

- Fatigue cracks may progress slowly in the initial stages, but crack growth will accelerate as the strength of the gear is progressively reduced, until forced fracture occurs.

The above points make a strong case for vibration monitoring techniques which can give reliable detection of fatigue damage at the earliest possible time. Before discussing the principles of SHL's analysis techniques, it is important to emphasise that 'vibration analysis' is not one technique, but covers a whole range of techniques. For example, two basic methods used to monitor gears and shafts in transmissions are:

(1) Power spectrum (FFT) analysis of vibration signals.

(2) The extraction of gear and shaft vibration signatures using the technique of signal averaging, and the analysis of these signatures using pattern based techniques.

SHL has pioneered method (2), this is the basis of the transmission health monitoring capability of the HUM system. It is worth commenting on two limitations of method (1) to explain why more sophisticated techniques are required:

(a) The components of the vibration signal which determine the overall signal level are rarely the ones that react to early failure. Gearbox vibration spectra are dominated by gear meshing tones, the early development of a gear fatigue crack will have little effect on these.

(b) Identification of any effects of defects such as modulation sidebands about meshing tones and harmonics can be very difficult for complicated gearboxes because of the large number of components appearing in the spectrum.

Simple spectrum analysis is not capable of producing reliable transmission health information to ensure improved airworthiness.

2.1.3 *Vibration analysis technology*

SHL's vibration analysis technology for gears and shafts can be described in terms of 3 basic processes as shown in Figure 2.1:

(1) **Primary analysis**

A vibration signal obtained from a transmission system will contain elements from all rotating components in the transmission. The objective of the primary analysis process is to extract from this signal only vibration generated by the components for which an analysis is to be carried out.

(2) **Secondary analysis**

The vibration signal is reduced to a 'vector' of fault-relatable indicators using intensive numerical analysis. The vector has a number of elements, which are a combination of 'expected fault' patterns and vibration energy measurements.

(3) **Tertiary analysis**

The tertiary analysis process is essentially one of interpreting the values of the indicators produced by the secondary analysis to determine the health of transmission components.

The 3 processes are described in more detail in the following sections.

2.1.3.1 Primary analysis

Gear and shaft vibration signatures are produced using a time domain signal averaging process, offering high noise rejection whilst retaining phase information.

Two sensors are required for synchronous averaging - (i) an accelerometer and (ii) a sensor (tachometer) giving phased locked information on the rotational speed of the transmission (see Figure 2.2).

An accelerometer mounted on the gearbox casing receives a raw vibration signal containing components from all the rotating elements in the gearbox. The tachometer signal can be obtained from a magnetic or optical device sensing a target mounted on one of the shafts in the drive train. The tachometer signal is processed electronically to produce a synthesised signal at once per revolution of the shaft for which a signal average is to be produced. This signal is used to synchronise sampling of the vibration data to the shaft rotation so that the resulting signature is made up of synchronous components only.

A fixed number of samples are taken from the vibration data for each revolution of the gear shaft. Samples from successive revolutions are summed together to produce a signal average. Only vibration components synchronous with the gear being analysed are retained during the summing process, all non-synchronous components are removed. The number of summing operations is controlled by a correlation process that determines when the averaging has succeeded in producing a stable signature.

The signal averaging process is repeated for each gear shaft in the transmission, producing a set of signal averages, each unique to a particular shaft.

2.1.3.2 Secondary analysis

The gear and shaft vibration signatures produced by the primary analysis are generally too complicated for visual interpretation. The purpose of the Secondary Analysis process is to reduce complicated signatures to a set of indicators that encode some degree of fault pattern or energy found in the average.

Different types of fault have different effects on a component vibration signature, the effect depends on the nature of the fault and the dynamics of the drive system. Using a combination of a theoretical understanding and practical experience of the effects of a fault, it is possible to predict the changes in a vibration signature resulting from different faults. Some of the changes are unique to a particular fault type, others may result from more than one fault. The secondary analysis indicators are targetted at detecting the different possible changes in vibration signatures. This approach provides the basic strength of the technology, it is not necessary to see real examples of every possible failure type to provide effective monitoring of these.

The indicators fall into two basic categories:

(a) Level analysis - the measure of absolute or relative energy levels of tones or frequency bands within the signature.

(b) Pattern analysis - 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.

Comprehensive transmission health monitoring requires a mixture of both pattern and energy indicators. Pattern indicators are effective detectors of the presence of a fault, vibration energy measurements provide useful additional information on the fault severity. Some of the 'energy' measurements can be in non-dimensional form.

The secondary analysis indicator algorithms implemented in the S61-N HUMS trial are listed in table 2.1, which also gives a brief summary of their nature and purpose.

2.1.3.3 Tertiary analysis

The purpose of tertiary analysis is to interpret the results of the secondary analysis process to:

(a) Determine the health of the transmission system.

(b) When the results indicate that damage has occurred, enable appropriate action to be taken to ensure that aircraft airworthiness is maintained.

The tertiary analysis process has two basic elements:

(1) The setting of indicator thresholds to enable the system to detect the initiation of a failure, whilst avoiding false alarms.

(2) Interpretation of the results to obtain information on the location, nature and severity of damage to allow appropriate action to be taken.

(1) *The setting of HUM system warning thresholds*

For some indicators thresholds can be set at well defined absolute levels. For example, for external shafts, the threshold for S01 can be set to manufacturers limits for imbalance. Absolute thresholds can also be set for indicators of localised gear tooth damage. These operate by comparing localised regions of a vibration signature with the remainder of the signature (Westlands M6* is included in this group).

The remainder of the indicators are interpreted by trending and thresholds must be based on 'no fault' levels.

Threshold setting for trended indicators

When setting thresholds it is necessary to consider two types of fault which the system should be capable of detecting:

(a) A maintenance/build fault, present from the commencement of transmission vibration monitoring.

(b) Damage developing during operation of the transmission.

Statistical techniques are used to set thresholds for the detection of developing damage by trended indicators, this gives maximum control over the false alarm rate. The basic approach used in the HUM system demonstrator is to calculate the mean and standard deviation of a sample of indicator values produced during initial monitoring of transmissions in an assumed healthy condition. Thresholds are set a certain number of standard deviations away from the mean level of 'no fault' results. These thresholds must obviously then be reviewed to check their suitability for providing airworthiness protection.

Fleetwide, or 'global' thresholds can provide airworthiness cover during the threshold 'learning' period and identify faults 'built in' to the gearbox during maintenance. Fault detection relies on the build fault producing results for a particular aircraft which are 'abnormal' when compared to the rest of the fleet (again statistical techniques can be applied).

(2) *Action following threshold exceedances*

Once indicator threshold exceedances have occurred it is necessary to identify a course of action to ensure aircraft airworthiness is maintained, whilst avoiding unnecessary operational penalties.

Information is required on (i) the location, and (ii) the nature and possible consequences of any transmission component damage detected.

Information on (i) is provided automatically by the system as the primary analysis process produces signatures specific to each shaft in the transmission. Information on (ii) can also be provided by the system owing to the fact that, by their nature, the different indicators contain some diagnostic data on the type and possible severity of damage.

The engineer responsible for reviewing the HUM data must have clear instructions on action to be taken following a HUM system indicator threshold exceedance. It is necessary to clearly define criteria for grounding an aircraft or rejecting a component.

The establishment of rejection criteria should be based on the following four elements:

(1) A theoretical understanding of the indicator algorithms and the expected relationships between faults and indicator behaviour.

(2) Practical experience of how the indicators have responded to real transmission component damage conditions. Helicopter experience is largely based on the results of transmission rig testing.

(3) Experience of how the indicators behave over an extended period of time on a fleet of aircraft and on different aircraft types. This will establish a baseline of 'normal' data for the different indicators.

(4) Agreement of rejection criteria with aircraft manufacturers, important from both a commercial point of view for 'power by the hour' operations and also for obtaining credit for HUMS.

Information on item (2) will increase as further rig testing of transmissions with seeded faults is carried out, and also lessons are learnt from any real 'arisings'. Information on (3) will rapidly expand as experience is gained from fleetwide fits of HUM systems. Aircraft manufacturers must become fully involved in HUMS to enable progress on item (4).

It is apparent from the above that rejection criteria will evolve with time as experience is gained and input is received from manufacturers. Initially simple rejection criteria will be set, based on either single threshold exceedances or simple combinations of exceedances for key indicators known to respond to potentially dangerous damage development.

2.1.4 *Application of the vibration monitoring technology to the S-61N HUM trials aircraft*

For the HUMS demonstrator the vibration analysis technology described in the previous sections was used to monitor the main drive train of the S-61 transmission system. This includes the main load path gears in the main rotor gearbox and the intermediate and tail gearboxes.

2.2 Rotor track and balance

It is generally accepted that there is a direct relationship between rotor induced helicopter vibration levels and helicopter reliability and maintainability. Minimising this vibration can lead to significant saving in maintenance costs (both labour and spare parts).

There are two main sources of rotor induced helicopter vibration:

(a) *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.

(b) *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. The sum of the individual blade responses produces hub moments and shears which excite airframe vibration. Blade passing frequency vibration is controlled by vibration absorbers.

HUM system action thresholds for main and tail rotor vibration should be set to existing aircraft manufacturers limits, although the data could be used to make adjustments to reduce vibration before these limits are reached.

2.2.1 *Potential airworthiness benefits of rotor track and balance*

At present the primary justification for including rotor track and balance functions in a HUMS is as a maintenance tool. However, the functions can also offer indirect airworthiness benefits by controlling and minimising rotor induced vibrations. For example, some evidence exists that reducing main rotor vibration levels can reduce failures of cockpit instruments or airframe damage, and can reduce aircrew fatigue. Control of tail rotor vibration will also offer airworthiness benefits. A high tail rotor imbalance can, if not corrected, lead to structural damage of the tail boom, but the vibration may not be be felt in the cockpit.

Widespread use of the SHL/Scientific Atlanta RADS-AT rotor track and balance equipment by both aircraft manufacturers and operators indicates that this function may also offer some direct airworthiness benefits. Some evidence exists that main rotor track and balance data can be used to detect main rotor head faults such as disbonding or degradation of elastomeric bearings, deterioration in the performance of lead-lag dampers and excessive play in control linkages (for example scissors assemblies or pitch link bearings). There is a need for research and development work on different aircraft types to establish; (a) the rotor head/blade faults which can be detected; (b) the sensor requirements to achieve this; and (c) the operating conditions under which data must be acquired.

2.2.2 *HUM trials system functions: Main rotor*

There are three conditions under which the HUMS was designed to acquire track and balance data:

(a) On the ground before the start of a flight the pilot can request main rotor balance measurements via the Pilot Control Interface (PCI). Measurements are the main rotor 1/rev and 5/rev amplitude and 1/rev phase in lateral and axial planes.

(b) When the aircraft is in a 'cruise' condition the system continuously monitors 1/rev and 5/rev amplitude and 1/rev phase.

(c) Following an indication of increased vibration a main rotor blade tracker can be fitted to the aircraft to enable the acquisition of both track and vibration data. Data can be taken at three flight conditions following prompts from the pilot via the PCI. The conditions are: On the ground (same as (a)), at 70 Knots and at 110 Knots (same as (b)).

2.2.3 *HUM trials system functions: Tail rotor*

The HUMS was designed to monitor tail rotor balance, measuring 1/rev and 5/rev amplitude and 1/rev phase, in axial and radial planes, under the following conditions:

(a) On the ground before the start of a flight, the data is acquired at the same time as main rotor balance data.

(b) The HUMS continuously monitors tail rotor balance when the aircraft is in a 'cruise' condition.

2.3 Engine monitoring system technology

2.3.1 *Introduction*

This section describes the engine monitoring functions used within the HUM system. A number of the functions are based upon BIHL's current operating procedures to enable comparisons to be made between the manually logged data and the information recorded by the HUM system.

2.3.2 *Power assurance and topping checks*

(1) **Power assurance**

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 can become impaired. Constant flying over open sea exposes the engines to salt spray ingestion, which can rapidly reduce the efficiency of the engines and consequently worsen fuel consumption. 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 days flying, whilst the engine is operating at 'cruise' power levels. The results are expressed in terms of gas generator speed (Ng) margin and power turbine inlet temperature (T5) margin. The engine power output is deemed acceptable when both the actual Ng and T5 are below the expected limits.

The expected limits for Ng and T5 are a function of the pressure altitude, outside air temperature, indicated airspeed (IAS) and type of engine inlet shielding fitted.

The on-aircraft HUMS equipment measures the following parameters 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)

The type of shield fitted to the engine intake has an effect upon engine performance and hence the PAC values obtained. The status of the engine inlet protection (FOD screen or ice guard) is uploaded to the on-aircraft HUMS equipment from the Ground Station Computer, as an item of configuration data. The PAC calculation then makes appropriate use of this data.

On the HUM system, PAC checks are manually initiated from a small cockpit mounted control panel (the PCI), once the helicopter is flying within the required operating envelope. The checks are performed in parallel with the existing manual procedure of recording the relevant parameters on PAC logsheets. After a period of data sampling, validity checks and four seconds of data averaging, the HUMS PAC results are calculated and stored in non-volatile memory within the HUMS on-aircraft equipment, for subsequent download to the Ground Station Computer. The validity checks ensure that the PAC calculation can only be made whilst the aircraft is operating within a valid envelope of operation for the PAC to be performed.

(2) **Topping**

Topping checks provide confirmation that the required engine output power can be achieved at high power (2.5 minute 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. An expected torque is calculated as a function of these input parameters, and then the torque margin is calculated in the manner described above. The torque margin result is stored in the non-volatile memory of the HUMS on-aircraft equipment, for subsequent download and inspection on the Ground Station Computer as for the PAC checks. During the Topping check the engine is operated at the 2.5 min rating level, whilst torque is not allowed to exceed a specified rating level.

Topping checks are manually initiated in the same manner as the PAC checks. The HUMS determines whether a PAC or a Topping result is to be produced by noting the value of T5 and Ng at the point of initiation. If both T5 and Ng are above certain values a Topping check is performed, otherwise a PAC is performed.

2.3.3 *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.

The HUMS provides a basic Low Cycle Fatigue (LCF) counting function for the gas generator spools on each engine. This function gives an accumulating total count for each engine, based upon the maximum (major cycle) excursion of gas generator speed (Ng) in each flight. The incremental count value for the LCF function on each flight is dependent upon the actual maximum speed achieved in that flight. The total accumulated LCF count for each engine is stored in non-volatile memory within the HUMS on-aircraft equipment.

2.3.4 *Limit exceedance*

Exceedances are monitored in accordance with BIHL's standard definitions of operating limits. Exceedances are only declared when a parameter exceeds the allowable time at a particular level, in one single excursion, in accordance with the established practice. A distinction is made between the engine start-up regime and the engine running regime. During an engine start the power turbine inlet temperature (T5) excursion is recorded if it exceeds a pre-set threshold value. The data recorded enables the shape of the excursion to be subsequently reconstructed when the recorded data is examined.

The HUMS monitors and records limit exceedances for both engines and transmission total torque. The parameters monitored are listed below.

For each engine:

- Engine torque (Tq)
- Power Turbine Inlet Temperature (T5)
- Gas generator speed (Ng)
- Free turbine speed (Nf)
- Engine lubrication oil temperature

and for the transmission:

- Total torque (sum of the two engine torques)

Two types of data are recorded in the HUMS on-aircraft equipment following the occurrence of a limit exceedance. Firstly, a separate counter is incremented indicating when each of the limit values for each monitored parameter is exceeded. Hence there are a number of counters for an engine, each reflecting the total number of exceedances which have occurred for each engine parameter/level combination. Secondly, data on each limit exceedance occurrence is stored in a number of records. These records log the time above each level, enabling a subsequent reconstruction of the shape of the exceedance profile to be made.

2.3.5 *General engine and aircraft statistics*

The HUMS calculates and records the following statistics:

- 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

Airframe Hours is defined as the total accumulated time that the helicopter is airborne, as indicated by the weight on wheels switch signal.

The Airframe Hours are used as the primary timebase for the recording of all HUMS data. Stored data is also tagged with time and date information for future reference.

The above data is stored in non-volatile memory within the HUMS on-aircraft equipment.

2.4 Oil analysis and debris monitoring

Monitoring of main gearbox oil and debris was conducted on the trial aircraft by use of both on-line and off-line techniques. The BIHL S61 fleet is subject to a Spectro Laboratories oil analysis programme, with samples taken from the main gearbox screen filter/chip detector port at 50hr intervals. An additional sample was taken from the two trial aircraft at the same time, for debris analysis and quantification by the Swansea Tribology Centre.

Both Spectro and Tribology data for the trial aircraft are recorded within the HUMS section of the Ground Station Computer (GSC). On the trials GSC the SOAP (Spectrographic Oil Analysis Programme) data from the remainder of the S61 fleet is entered into a separate, complementary SOAP database, which is also on the GSC.

2.4.1 *Oil analysis*

The method employed by Spectro Laboratories for analysis of the BIHL gearbox samples evaluates the quantity of very small particles (<1 to about $10\mu m$) present within an oil sample. Spectro Laboratories use the Inductively Coupled Plasma technique for sample analysis. This technique evaluates the elements present within a sample by burning the oil at extreme temperature, some 10,000 deg C, and measuring the light spectrum emitted.

This system is capable of detecting concentrations of elements present in extremely small amounts, in the case of iron as low as 0.003ppm, (Parts per million). For practical use a tolerance of 0.01ppm is employed.

2.4.2 *Debris analysis*

The two Swansea techniques employed during the trial were the Rotary Particle Depositer (RPD), and the Particle Quantifier (PQ). These systems are used to monitor oil debris particles from about $1\mu m$ upwards. In very general terms, as wear or damage progresses, the size of particle produced will tend to increase.

As the Spectro analysis is capable of monitoring only the smaller particles, the situation can arise where the Spectro measured levels are apparently falling, due to larger particles beyond the detection range of this method being produced. At this stage the Swansea techniques become valuable, quantifying and classifying wear particles into specific types.

The RPD extracts debris from a sample by a combination of magnetic, centrifugal and gravitational forces. This is achieved by gradually feeding the oil sample onto a glass slide, which is fixed onto a rotating magnet assembly. The oil is washed off the sample debris with tetrachloroethylene, a mild solvent. The debris from the sample is left as a deposit on the glass slide, suitable for optical microscope examination. The micro-scope operator is able to classify the amount and type of debris present, ie non-ferrous, cutting wear, fatigue chunks, etc. The size of individual particles may also be measured, which can serve to give an indication as to the stage which wear or damage has progressed to.

The PQ is a magnetometer type of instrument, and gives a value, the PQ Index, relating to the quantity of debris present within the sample. The PQ can quantify a sample in any one of 3 conditions:

(1) As an RPD slide prepared as described above

(2) As a deposit on a millepore filter

(3) As debris in suspension within an oil sample contained in a small plastic pot, the "pot method" was used in the trial.

The PQ Index is a trending indicator, changes in the wear situation with running time are reflected by changes in the PQ Index. It is possible for PQ Index to be measured on site using a portable analyser available from Swansea Tribology Centre, the PQ 90. In circumstances where timely transport of samples to a laboratory is impractical, (for example a long term contract in a remote overseas area, such as BIHL has held in the past in India and China), an on site PQ measurement capability would provide an acceptable oil monitoring function.

2.4.3 *On-line oil debris monitoring*

On-line oil debris monitoring took the form of counting chips, considered as significant particles which can bridge the gap of a chip detector, and the discharges from a Tedeco Zapper fuzz burner (which is capable of removing, by capacitance discharge at the detector gap, the fine wear particles or fuzz as they accumulate on the detector).

A Tedeco Zapper fuzz burner chip detector was installed in the main gearbox, and the standard Sikorsky chip detectors were retained in the intermediate and tail gearboxes. All chip detectors and the zapper unit were connected directly to the HUMS, where chip and zapper discharge counts were recorded separately.

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

TABLE 2.1 : Vibration secondary analysis indicators implemented in the S61-N HUMS trial

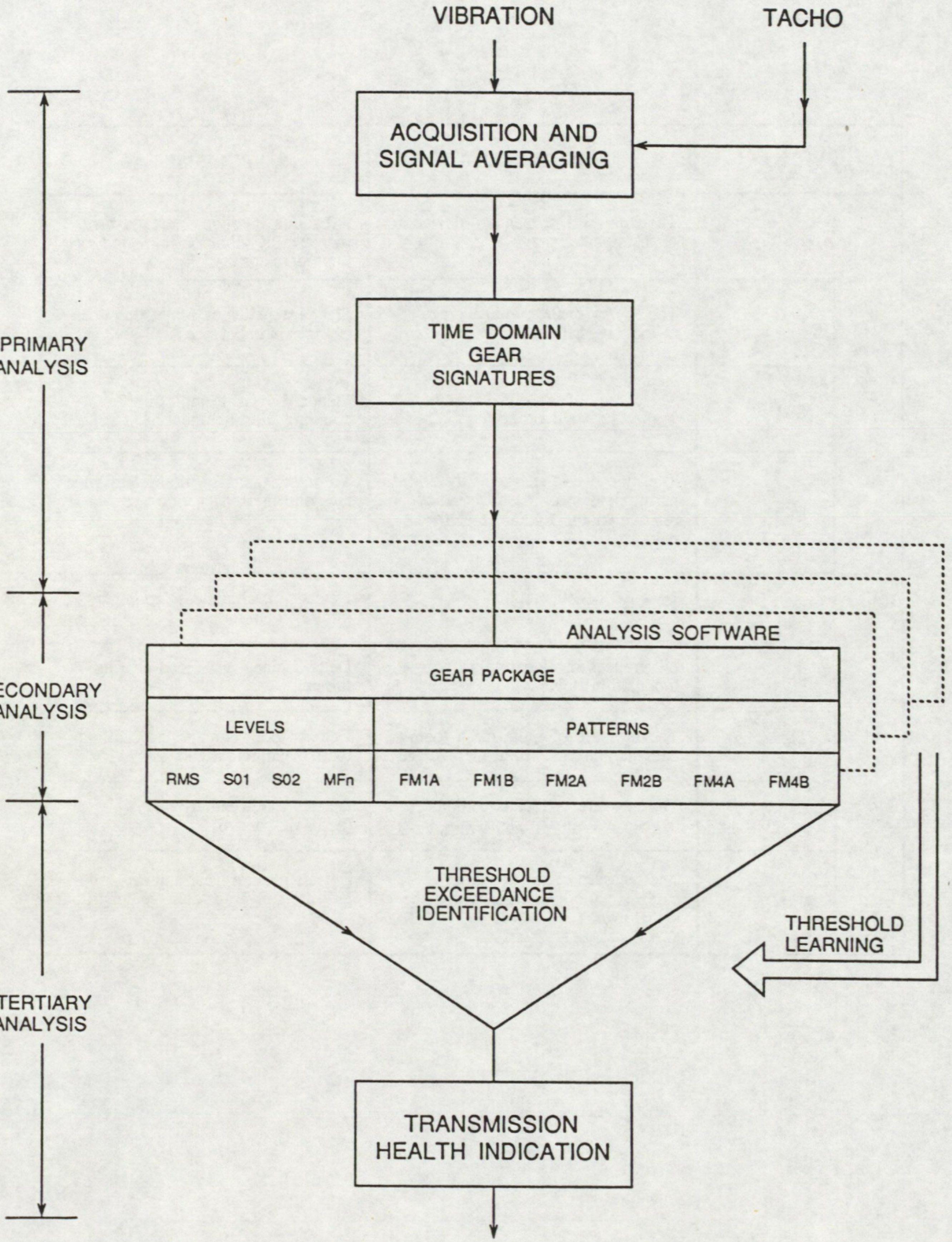


FIGURE 2.1 : HUMS vibration analysis processes

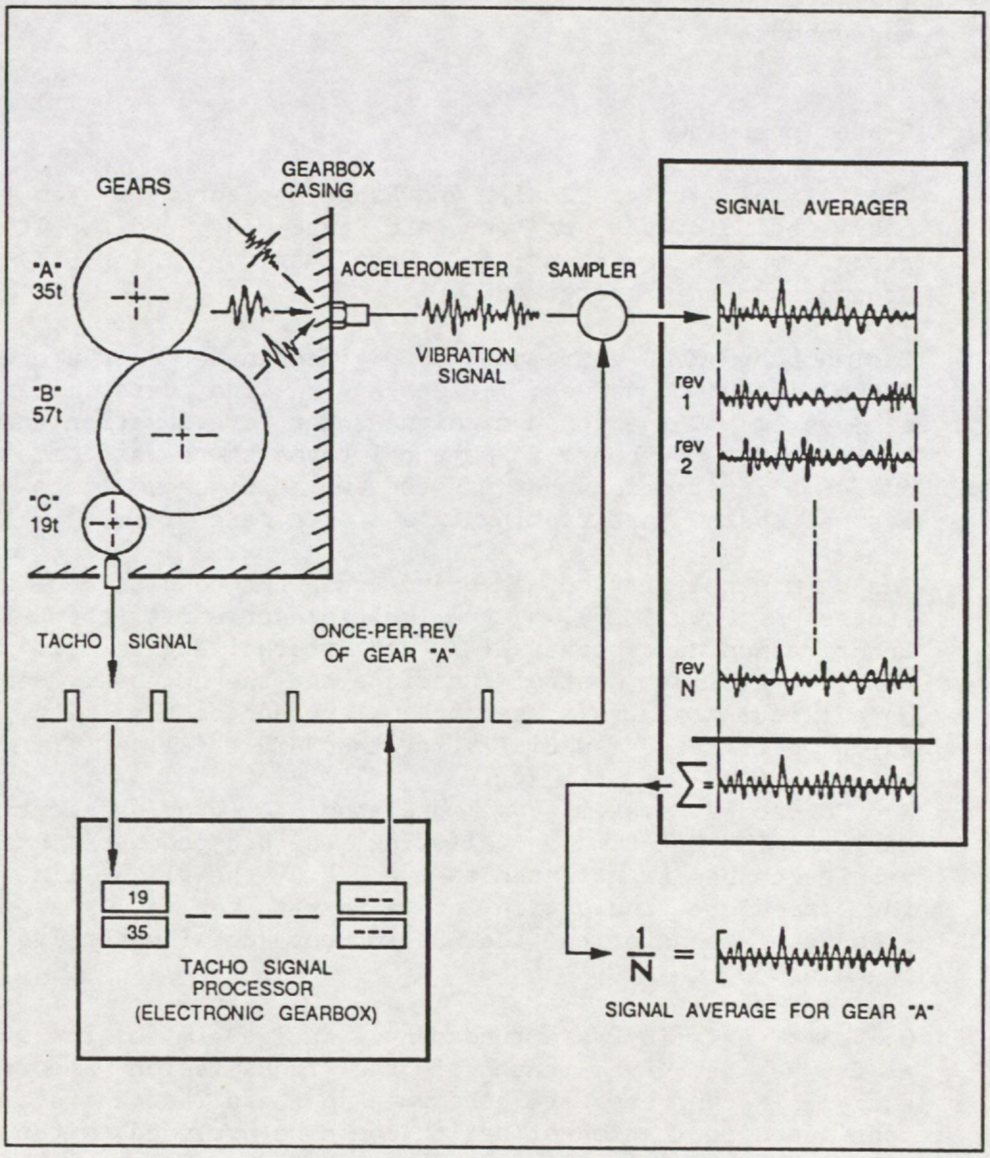


FIGURE 2.2 : Gear signature acquisition

3.0 HUM SYSTEM DESCRIPTION

This section presents an overview of the main components of the HUMS and their functions, followed by a more detailed description of the HUMS airborne and ground-based hardware. The section also describes the installation of the aircraft equipment.

3.1 System overview

The CAA S61N trial Health and Usage Monitoring System (HUMS) consisted of a set of on-board equipment and two items of ground support equipment; a Data Retrieval Unit (DRU) and a Ground Station Computer (GSC).

The on-board HUMS equipment was divided in terms of processing logic into two halves: the engine and data management sub-system and the transmission and rotor vibration analysis sub-system, although in physical terms there was commonality and some interaction between the two. Figure 3.1 shows this logical system partitioning in a diagrammatic form.

The permanently fitted on-board equipment consisted of a Main Processing Unit (MPU), two multiplexer units (the External Transmission Multiplexer ETMX and External Engine Multiplexer EEMX), a Pilot Control Interface and the necessary sensors. Some existing aircraft sensors were used together with others which were fitted especially for the HUMS trial.

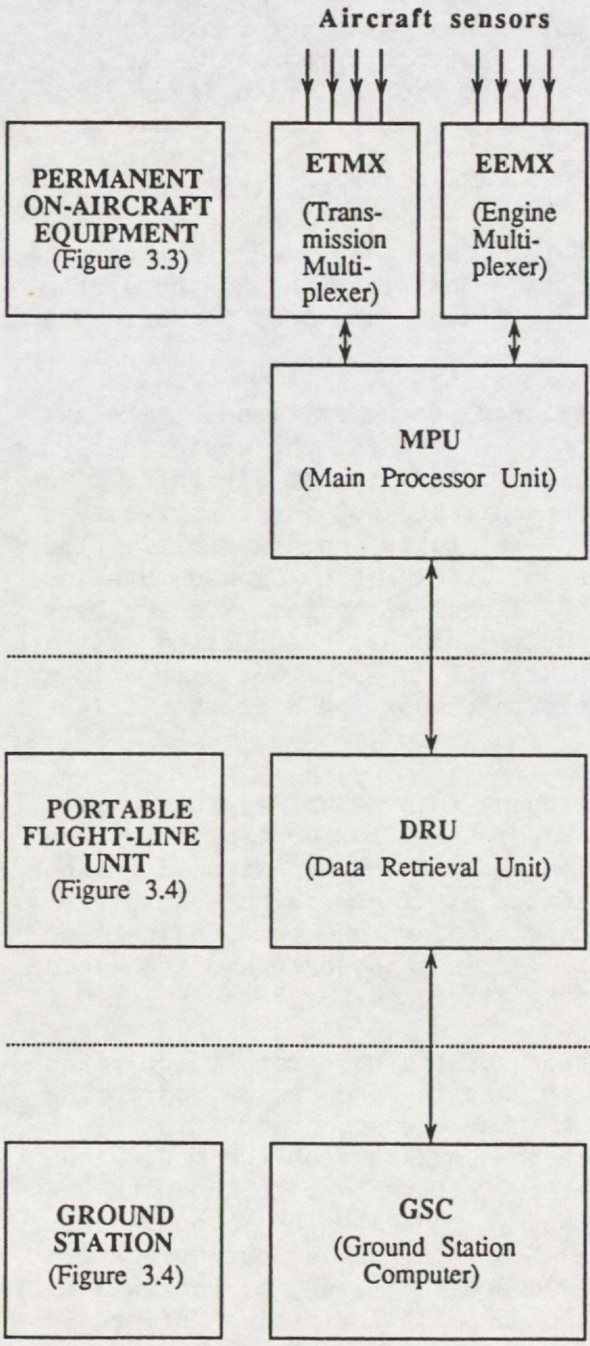
The on-board system was designed to provide continuous analysis in real-time, allowing the pre-processed analysis results to be transferred to the DRU by the flight line staff for immediate indication of aircraft health, and then subsequent transfer to the GSC for more detailed analysis and trending.

On-board analysis was a fundamental design aim for the system, as it was perceived that if the transmission and engine analysis techniques were performed in the airborne system, a continuous indication of health could be provided, without the reliance on additional ground support equipment. Thus the aircraft health status could be made available to give an immediate turn round of the aircraft when it is operating away from its maintenance base, or provide the possibility in the future of an in-flight warning. The on-board analysis of vibration data has only been made possible by recent developments in micro-processor technology, providing sufficient on-board processing power.

The following diagrammatic representation of the system identifies the major system components and their functions, the components are illustrated in Figures 3.2, 3.3 and 3.4.

3.1.1 *Major HUM system components and functions*

COMPONENT **FUNCTION**



- Multiplexing
- Signal conditioning

- 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

- 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

- 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

3.2 Airborne hardware

3.2.1 *Introduction*

The physical nature of the airborne system evolved from the consideration of a number factors associated with the trial.

The trial programme had an incremental plan for including the various analysis functions. The system was therefore designed to be modular, with the ability to be reconfigured for different or enhanced operations with minimal hardware changes. This was achieved by physically partitioning the system into a number of functional self-contained processor modules, linked together through various serial data interfaces. As each module was designed to operate independently of the other parts, modifications to the system functionality were implemented without the need for hardware changes.

Although the system was developed for a trial on a Sikorsky S61N aircraft, consideration was given at the system design stage to how it could be modified for different aircraft. To ensure that the system would be suitable for any aircraft type the airborne system operation is fully configurable. The configuration data is created within the Ground Station Computer and loaded into the airborne system via the Data Retrieval Unit. This not only enables the system to be re-configured for different aircraft types, but also allows the sequence of analyses performed under the different flight conditions to be optimised.

The trial system was partitioned into four separate units: The Main Processor Unit (MPU), the Pilot Control Interface (PCI) and two sensor conditioning units - the External Engine Multiplexer (EEMX) and the External Transmission Multiplexer (ETMX) - performing signal conditioning on the engine and transmission sensors. Figure 3.5 is a photograph of the four items comprising the permanently fitted on-board equipment.

The MPU controls the operation of the on-aircraft equipment and performs all the on-board health and usage monitoring functions. The MPU controls the operation of ETMX via a serial datalink. In response to commands from the MPU, the ETMX selects each accelerometer in turn, together with the appropriate tachometer, and routes the conditioned accelerometer signal to the MPU for subsequent vibration analysis. The signal from each accelerometer is processed in turn, in accordance with the schedule of activities defined in the software within the MPU.

The EEMX measures the main parameters on each engine and some airframe parameters, providing a continuous stream of digitised data to the MPU.

The PCI is a small cockpit mounted panel which provides a means of manually initiating some of the tasks performed by the HUMS. It also provides a visual indication of the progress of these functions.

3.2.2 *External Transmission Multiplexer (ETMX)*

The ETMX is shown on the left of Figure 3.5. The ETMX provides local signal conditioning for the sensors associated with the transmission vibration analysis and chip detection in the lubrication oil. It conditions sensor signals from the vibration accelerometers, shaft speed tachometers and oil chip detectors, providing high level buffered output signals to the vibration monitoring sub-system within the MPU. Hence the ETMX is primarily a remotely controllable multiplexer system.

To meet the needs of the transmission vibration monitoring sub-system, the ETMX has sufficient sensor input capacity to accommodate the requirements of a typical large single rotor aircraft. The ETMX accepts the following input signals:

- Up to 14 Accelerometers
- Up to 3 Tachometers
- Up to 6 Chip detectors / discrete inputs

Within the ETMX there are four functional parts:

(1) Microcontroller and memory
(2) Accelerometer multiplexing and signal conditioning path
(3) Tachometer multiplexing
(4) Chip detector measurement

(1) **Processor and memory**

Processing is performed by a microcontroller which is a highly integrated processor containing many facilities. These include a 10 bit Analogue to Digital Converter (ADC) with eight channel multiplexer, frequency measurement and serial data communications facilities.

(2) **Accelerometer multiplexing and conditioning**

The ETMX multiplexes the accelerometer inputs down to two differential analogue output channels, for transmission to the MPU. For the S61N HUMS application, a total of nine integral charge amplifier accelerometers are used; seven on the main gearbox and one each on the intermediate and tail gearboxes.

The signal path between the accelerometer and the output channel contains the following elements:

- Accelerometer drive power
- Differential multiplexing
- Programmable gain amplification
- Programmable high pass filtering
- Signal peak detection
- Automatic gain range selection logic

The accelerometer channel selection is controlled by the MPU, via a serial datalink. The MPU also controls the high pass filter setting, appropriate to the particular vibration analysis task being undertaken. The ETMX automatically selects the most appropriate gain for the selected channel.

(3) **Tachometer multiplexing**

Similarly, the ETMX multiplexes tachometer inputs down to one channel for output to the MPU. Multiplexer Channel Selection is controlled by the MPU via a serial data link. For the S61N HUMS application three tacho channels are used.

(4) **Chip detection**

Chip detection facilities are provided for the Main, Intermediate and Tail gearboxes. The ETMX is provided with six chip detection channels, four of which are used for this application.

Two channels are used for the Main Gearbox (MGB), one for the detection of the presence of a chip and the other to count the number of 'Zap' pulses generated by the Tedeco 'fuzzburner' fitted on the MGB. The Intermediate and Tail Gearboxes are fitted with conventional electric chip detectors and the ETMX uses one channel for each of them.

Chip detect status information is conveyed to the MPU via a serial datalink.

3.2.3 *External Engine Multiplexer (EEMX)*

This unit is very similar in construction to the ETMX. It is shown at the right of Figure 3.5. Internally it uses the same micro controller as the ETMX, but has a different set of analog input circuits to meet the requirements for interfacing with the engine and airframe sensors.

The function of the EEMX is to provide local measurement, validation and digitisation of engine and airframe parameters which are then transmitted as a serial data stream to the engine monitoring sub-system within the MPU. Hence the EEMX is different from the ETMX in that it digitises all input signals before sending the resulting data to the MPU.

The EEMX operates autonomously once the on-board HUM system has successfully passed its power up self test. Unlike the ETMX, the EEMX does not require commands to be sent from the MPU to control its operation.

High impedance buffering and fault protection is provided to ensure that the connection of the EEMX input circuits across existing aircraft sensors does not affect instrumentation readings or provide a hazard.

The EEMX interfaces with the following sensors for the S61N application:

(1) **Engines 1 and 2: (Existing sensors)**

- Gas generator speed (Ng1 and Ng2)
- Free turbine speed (Nf1 and Nf2)
- Engine output torque (Tq1 and Tq2)
- Power turbine inlet temperature (T51 and T52)
- Oil temperature (OT1 and OT2)

(2) **Air data: (additional sensors)**

These were added for the purposes of the HUMS trial and therefore the sensors are not shared with existing aircraft instrumentation.

- Outside air temperature (T2) - A platinum resistance bulb was fitted for the HUMS trial.
- Altitude (ALT) - This is obtained from a Penny and Giles Air Data Unit.
- Indicated Airspeed (IAS) - This is also obtained from the Penny and Giles Air Data Unit.

3.2.4 *Main Processing Unit (MPU)*

The Main Processor Unit was designed to perform all of the on-aircraft processing and analysis described within Section 2. The system performs four basic functions:

(a) Analysis of vibration signals

(b) Analysis of engine/aircraft signals

(c) Storage of analysis results and comparison against thresholds

(d) Transfer of data to and from the Data Retrieval Unit

The MPU is packaged in an ARINC 1/2 ATR sized chassis, containing three Printed Circuit Boards and a separate power supply.

The MPU is functionally divided into two halves, the transmission and rotor vibration analysis sub-system, and the engine and data management sub-system, although physically there is commonality between the two functions.

The engine and data management sub-system provides the interface to the DRU, performs the engine monitoring functions, provides the storage for the analysis results and, based upon the status of aircraft and engine sensors outputs, determines the mode of operation for the MPU. This sub-system consists of a single module within the MPU known as the Data Management Card (DMC). The DMC is interfaced to the EEMX which processes the engine and aircraft signals. Configuration data which controls the sub-system is held within non-volatile memory on the DMC. The engine analyses are performed when the correct analysis conditions are detected by the DMC.

The transmission and rotor vibration analysis sub-system consists of two modules within the MPU; a signal conditioning system - the Vibration Data Acquisition Card (VDAC), and the vibration analysis system - the Transputer Processor Card (TPC), which in turn controls the ETMX. Storage of the analysis results is performed by the DMC module, however all configuration data which determines the sub-system operation is stored within non-volatile memory on the TPC. The transmission vibration analyses are scheduled by the TPC after the DMC has identified the correct analysis conditions from the aircraft and engine sensors. The analysis result interpretation function (ie the comparison of results against stored thresholds) is performed within the DMC module.

(1) **Vibration Data Acquisition Card (VDAC)**

The function of the VDAC is to perform the basic signal processing required within the transmission and rotor vibration analysis sub-system. These operations are performed under the request of the TPC, and process signals selected by the ETMX.

The VDAC can be divided into four functional elements:

(a) Vibration acquisition sub-system
(b) Tachometer conditioning sub-system
(c) Tracker interface sub-system
(d) Programmable Digital Signal Processor (PDSP) sub-system, which controls the three other sub-systems.

The VDAC uses fixed frequency sampling (12 bit Analogue to Digital Converter) and anti-alias filtering. A programmable digital signal processor (PDSP) then reduces the sampling rate down to the frequency required by the current analysis in a 'decimation' process.

The tachometer conditioning sub-system is designed to shape the different tacho inputs into a digital signal that can be processed by the TPC. The system also routes the conditioned signal through to the tracker interface.

The tracker interface was designed to operate with the standard SHL automatic blade optical tracker (ABT) used in the Rotor Analysis and Diagnostic System (RADS). The tracker interface records a series of times when then ABT detects the passing of a main rotor blade.

The PDSP controls all of the other sub-systems within the VDAC. The VDAC does not require any external configuration data, all parameters used with the different DSP algorithms are held in memory on the module.

To achieve data transfer between the VDAC and the TPC of the digitised data, the PDSP uses a link adapter. This is a device developed by Inmos to enable other micro-processors or peripherals to communicate directly with a transputer.

(2) **Transputer Processor Card (TPC)**

The TPC module divides into two functionally separate systems, one which monitors the inputs from the DMC to identify what operating mode the MPU is in, and a second which performs the analysis tasks. These sub-systems are implemented on two different transputers. The control function is implemented within a 'master' transputer whilst the analysis functions are implemented within a 'slave' transputer.

The Mater transputer has memory for code and data storage and an off-board link to the DMC. The Slave transputer has memory for code storage, data execution, and storage of configuration data, two serial interfaces, an off-board link to the VDAC, and an event interface for processing tacho signals.

(3) **Data Management Card (DMC)**

The main function of the DMC is to perform the engine monitoring tasks, coordinate and distribute flight regime information and manage all of the results data produced by the on-board vibration and engine monitoring sub-systems.

The DMC contains a processor with memory for code storage, data execution, and for storage of results and configuration data. In addition the card contains serial interfaces, an off-board transputer link, a battery supported day/date clock, and a 16 channel analogue interface with 10 bit ADC.

The 16 channel analog interface is used to provide a discrete signal input measurement capability within the MPU. Some of the signals monitored provide a fall-back capability in the event of a loss of one of the signals from the EEMX.

The input channels are allocated to the following signals:

- Weight on Wheels status
- Rotor Brake status
- Parking Brake status
- Engine no.1 Oil Pressure status
- Engine no.2 Oil Pressure status
- Engine no.1 Air Bleed status
- Engine no.2 Air Bleed status
- Interface to PCI (4 channels)
- Rotor Tracker connection status
- DRU connection status
- VDAC watchdog status
- TPC watchdog status
- Internal calibration signal

(4) **MPU power supply module**

The MPU contains a DC-DC power supply which converts the incoming 28V DC supply to the voltage rails required by the electronics within the VDAC, TPC and DMC cards, ie 5V for logic, +12V and -12V for analog electronics. Total power consumed by the MPU is approximately 25 Watts.

(5) **Signal conditioning card**

The discrete input signals and DC power input first pass through this card before reaching the circuits inside the MPU. The signal conditioning provides fault buffering from the aircraft circuits and power input transient suppression, to accommodate the spikes and surges in the power provided by the aircraft.

3.2.5 *Pilot Control Interface (PCI)*

For the HUMS trial it was necessary to provide a means of manually initiating certain tasks on the system:

PAC and Topping checks
Ground based rotor track & balance measurements
In-flight rotor track & balance measurements

The purpose of the PCI is to provide discrete event inputs into the HUMS to initiate the above functions, when the operating regime of the aircraft is suitable for the particular function. The PCI also provides status information relating to the selected functions by means of in-built indicator lamps.

The PCI is shown at the bottom of Figure 3.5. It contains a disable/enable switch, a select function switch, an acquire data switch, six function indicator lamps and one lamp to signify acquisition in progress.

3.2.6 *Additional sensors fitted for the HUMS trial*

Five separate types of additional sensors were used with the trial system:

(1) Accelerometers
(2) Tachometers
(3) Main rotor blade tracker
(4) An Air Data Unit, sensing barometric altitude and airspeed
(5) An Outside Air Temperature probe

Cables from the sensors on the transmission were routed to the processing units through a specially installed connector on the main transmission deck.

(1) **Accelerometers**

The accelerometer selected for use with the trial system was the Endevco 7251-10, with an integral charge amplifier. Accelerometers were mounted on a standard Endevco mount block, a small hexagonal stainless steel block with a tapped hole for the accelerometer mount bolt. The mount blocks were bonded to the gearbox casings.

The following list describes the location of the accelerometers fitted to the S61N trials aircraft:

A MGB port freewheel unit
B MGB stbd freewheel unit
C Top of MGB input casing
D MGB top cover
E MGB ring gear aft
F MGB ring gear
G Underside of MGB casing
H IGB casing
I TGB casing

Figure 3.6 shows the locations of the accelerometers and tachometer on the main gearbox.

(2) **Tachometers**

The trial system employed three different tachometers, one each on the main rotor and tail rotors, and a third on the main gearbox.

The main rotor tachometer is required to generate a phase signal for rotor track and balance. The system uses an Electro Corp 3030 inductive tachometer. The tachometer probe was installed in the standard Sikorsky position on the main rotor stationary swashplate, as used for the Chadwick track and balance equipment employed by BIHL for the S61.

The tail rotor tachometer is used to provide a phase signal for rotor balance. As an inductive tachometer cannot be mounted conveniently, the system uses an optical tachometer designed by Scientific Atlanta for the RADS-AT rotor track and balance system. The tachometer sights on reflective tape attached to one of the tail rotor blades.

The high speed main gearbox tachometer provides the rotational speed signal used for the vibration signal averaging process. The tachometer probe used is the Electro Corp 3015M. The probe was installed on a bracket attached to the front of the main gearbox, the once-per-rev signal was produced by a target fitted to the rotor brake disc attachment flange.

(3) **Main rotor blade tracker**

The system is designed to operate with the SHL Automatic Blade Tracker (ABT), used as part of the RADS-AT system. It was intended that the tracker would be installed only for test flights. The tracker is mounted on a BIHL designed bracket attached to the battery box cover on the nose of the S61. When fitted, the tracker is plugged into a connector permanently installed inside the battery box.

(4) **Air Data Unit (ADU)**

A Penny and Giles D60060 Air Data Unit was installed on the cabin floor forward of the yaw control pedals. Barometric altitude and airspeed are sensed directly from the co-pilots instrument supply lines.

(5) **Outside Air Temperature (OAT)**

A resistance type OAT probe is installed on the outside of the cabin roof, and is supplied with DC power from the EEMX.

3.2.7 *Existing aircraft sensors used in the HUMS trial*

The existing aircraft instrument sensors were used for engine parameters of:

(1) T5 (K type thermocouple)
(2) Nf and Ng (Variable frequency tachometer generator)
(3) Torque (3 phase synchro)
(4) Engine Oil Temperature (Variable resistance probe)

The existing aircraft instrument wiring for these sensors was re-routed to additional terminal blocks, where parallel cables were installed which supplied the signals to the EEMX in addition to the existing instruments.

The standard Sikorsky Tedeco chip detectors in the tail and intermediate gearboxes were directly connected to the ETMX (chip warning lights are not installed on British Civil Registered S61s). A Tedeco "zapper" fuzzburning chip detector was installed in the main gearbox of one trial aircraft, G-BEIC. The zapper control unit was mounted inside the aircraft cabin below the main gearbox.

3.2.8 *HUM System Installation*

Design, certification, and installation of the trial system was carried out on both trial aircraft by BIHL at its Aberdeen base.

A partition was installed in the aft baggage bay, with a shelf on which the units were mounted. In this location the processing units were readily accessible for installation and removal. The MPU used a standard 1/2 ATR tray, the multiplexers were bolted directly to the shelf in the compartment formed by the partition within the baggage bay. Cable routing, securing and specification of additional cables and hardware was carried out in accordance with established standard practices.

The complete installation (including all sensors and wiring) weighed a total of 84 lbs. The production system is an integrated HUMS/FDR, this combination allows the weight of the HUMS function to be reduced to the order of 10% of the trial system weight.

3.3 Ground-based hardware

The airborne equipment is supported by two ground-based systems, designed to give different levels of support to the HUMS. The first line of support was designed for use by the flight line engineers, giving a simple go/no go clearance for the aircraft. The second line of support allows investigation of any detected exceedance and provides for long term planning through integration with other systems. To facilitate the different levels two different ground support systems were developed, namely:

(1) *Data Retrieval Unit (DRU)*

A portable battery powered computer, interfacing directly to the airborne system and permitting limited access to analysis results. A single unit can support a number of aircraft. This unit can also be used in flight or on the ground as a piece of test equipment.

(2) *Ground Station Computer (GSC)*

A PC based database system which transfers data to and from the airborne system via the DRU. This stores both airborne system configuration data and all analysis results downloaded from the airborne system.

Both the DRU and GSC are capable of handling data from different aircraft types operating in a fleet. The DRU and GSC are shown in Figure 3.4.

3.3.1 *Data Retrieval Unit*

The DRU is the main interface between the flight line and the HUMS. The DRU is used to download and display analysis results produced by the airborne system, and upload configuration data to the airborne system. It is a rugged simple to use system, capable of displaying to the flight line personnel information upon which they can act. The information displayed is mainly text, but some information can be more clearly displayed using graphics. The DRU fulfilled the following requirements:

(1) The unit should be portable and battery powered.

(2) The unit should be capable of displaying both text and graphics.

(3) The unit should be rugged and environmentally sealed.

(4) The unit should have a simple user interface, suitable for operation in a gloves on environment.

(5) The unit should be suitable for operation in low ambient light.

(6) The unit requires interfaces to communicate to the airborne system, and the GSC.

Within the SHL Rotor Analysis and Diagnostic System (RADS) project a portable battery powered computer was developed specifically for use in a helicopter environment. This unit was chosen as the DRU for the HUMS trial. The unit used was the Mk I version of the RADS-AT Control and Display Unit (CADU), and incorporates:

(1) A simple touch-key keyboard.

(2) A graphic liquid crystal display capable of displaying text and graphics, with a backlight facility which allows the display to be read in zero ambient light conditions.

(3) A Motorola 68000 micro-processor with 2 Mbytes internal non-volatile memory, and 1 Mbyte program storage.

(4) Two serial interfaces, one line is used for communicating with the GSC, whilst the other is used to communicate with the MPU.

3.3.2 *Ground Station Computer*

The Ground Station Computer (GSC) is designed to allow an operator to set up the configuration of the airborne system and then to view the results from the aircraft. The GSC requires large databasing facilities in order to handle all of the information, which must also be readily accessable to users.

SHL, during involvement in different machinery monitoring programs prior to this project, identified that the interface between the user and the system was critical if full and effective usage of the system is to occur. SHL decided that the following ergonomic features would be required:

(1) The user should require no specialised knowledge of the database or the operating system.

(2) Data should be organised hierarchically around the maintainable units in the aircraft, for example the aircraft is made up of engines, gearboxes, and rotors, and a gearbox is made up of shafts, which in turn have gears etc.

(3) Selection of different options or data within the system should be achieved through menus.

(4) Data input to the system by the user should be input in standard forms similar in nature to those used in any existing paper systems.

(5) Data from the system should be displayed in a familiar form, similar to standard reports within existing maintenance or flight manuals.

(6) When displaying alarm information, the operator should be prompted to the source of the alarm in relation to the complete system being monitored.

(7) The operator should be able to access data simultaneously in order to compare different parts of the database.

(8) The system should be implemented upon low cost hardware.

To achieve this goal SHL developed the Plant Operators Maintenance Management System (POMMS), around which a user interface for monitoring systems can be built. POMMS uses a proprietary hierarchical database which runs under a multi-tasking operating system. The main feature of the database is that to interrogate the data the operator uses a series of graphical diagrams, known as mimics, representing the system under test. The multi-tasking system allows the operator to run a number of different data entry or display options simultaneously.

This GSC software was developed from POMMS and is configured to run upon an 80386 IBM/PC or clone, with a least 2 Mbytes of RAM, a 60 Mbyte hard disc, EGA or VGA colour graphics card, and a mouse. The computer used for the HUMS trial ground station was a Compaq 386 PC.

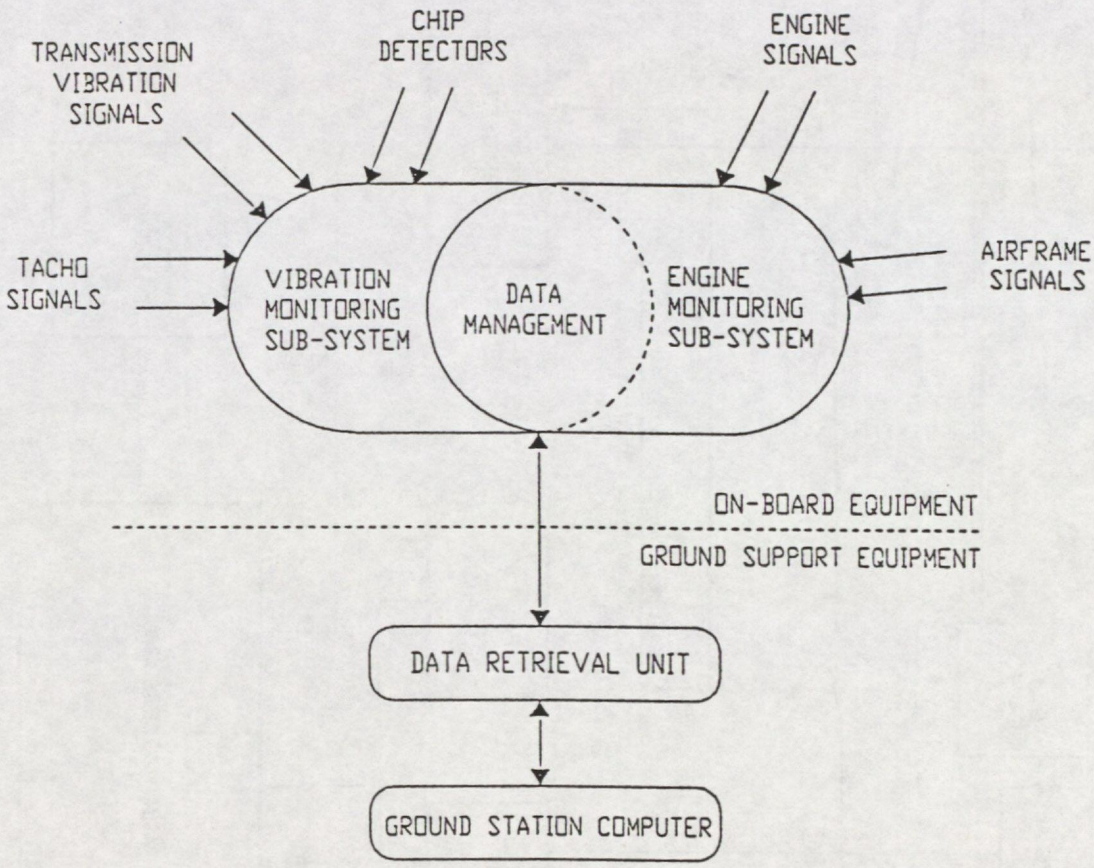


FIGURE 3.1 : HUMS - Logical partitioning of system

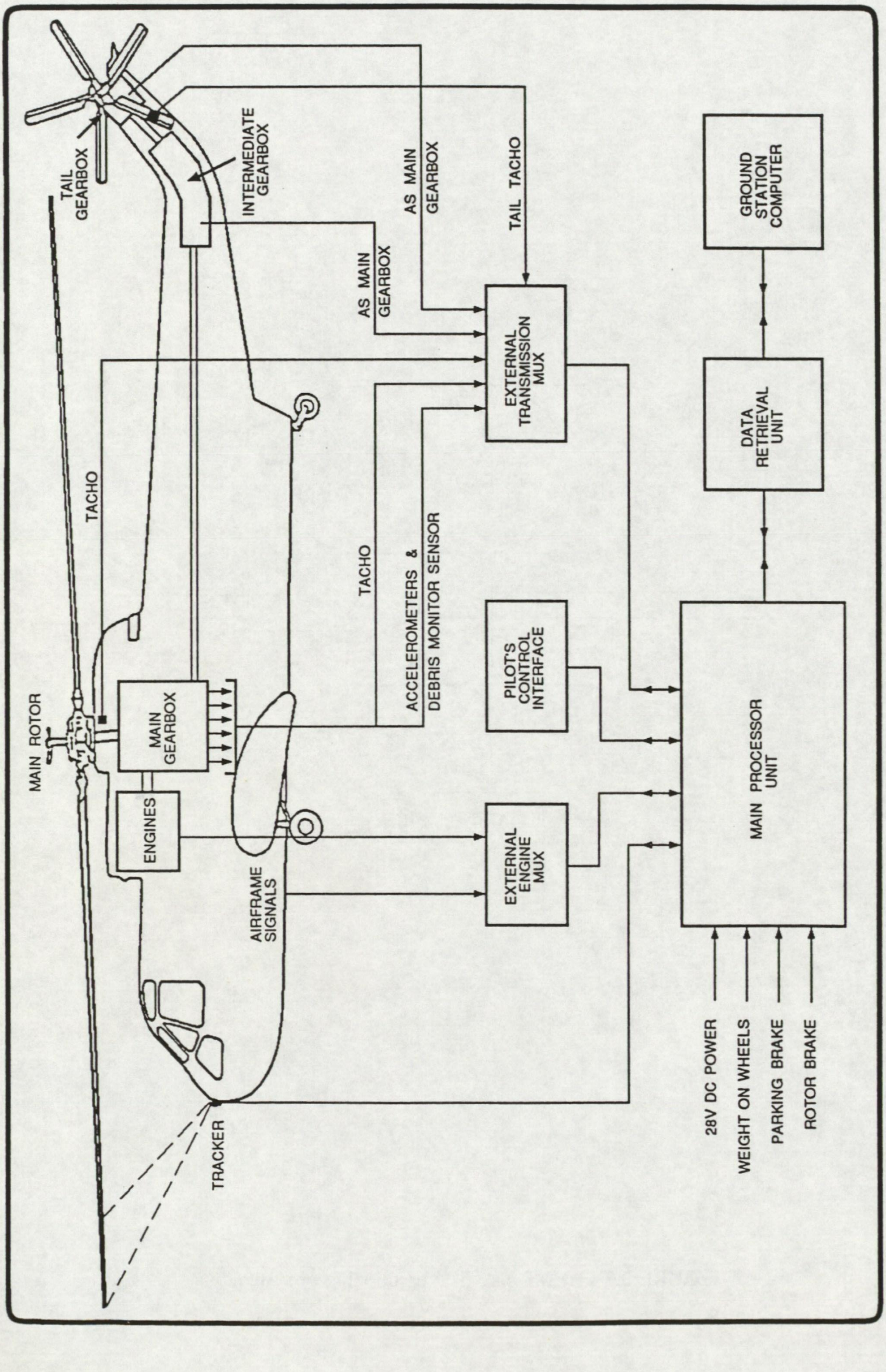


FIGURE 3.2 : Overall system block diagram

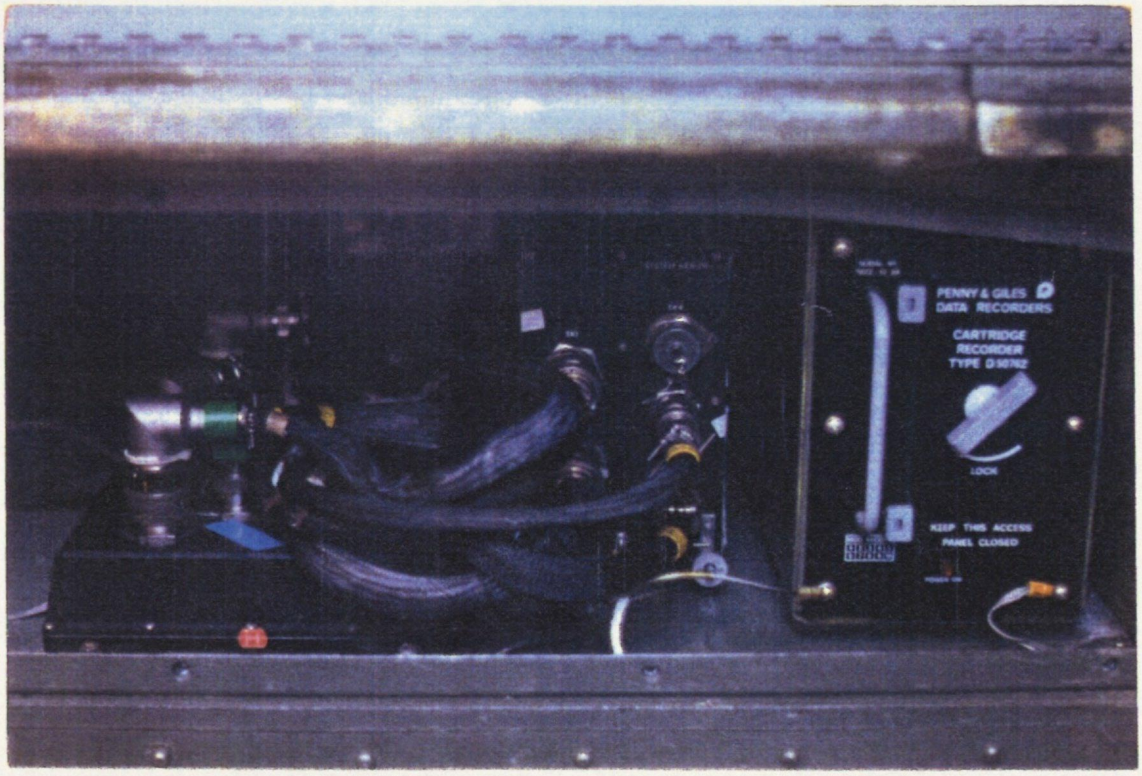


FIGURE 3.3

TOP: HUMS trial aircraft G-BEIC

BOTTOM: EEMX and ETMX (left), MPU (centre), Engine tape recorder (right and not part of permanent HUM system)

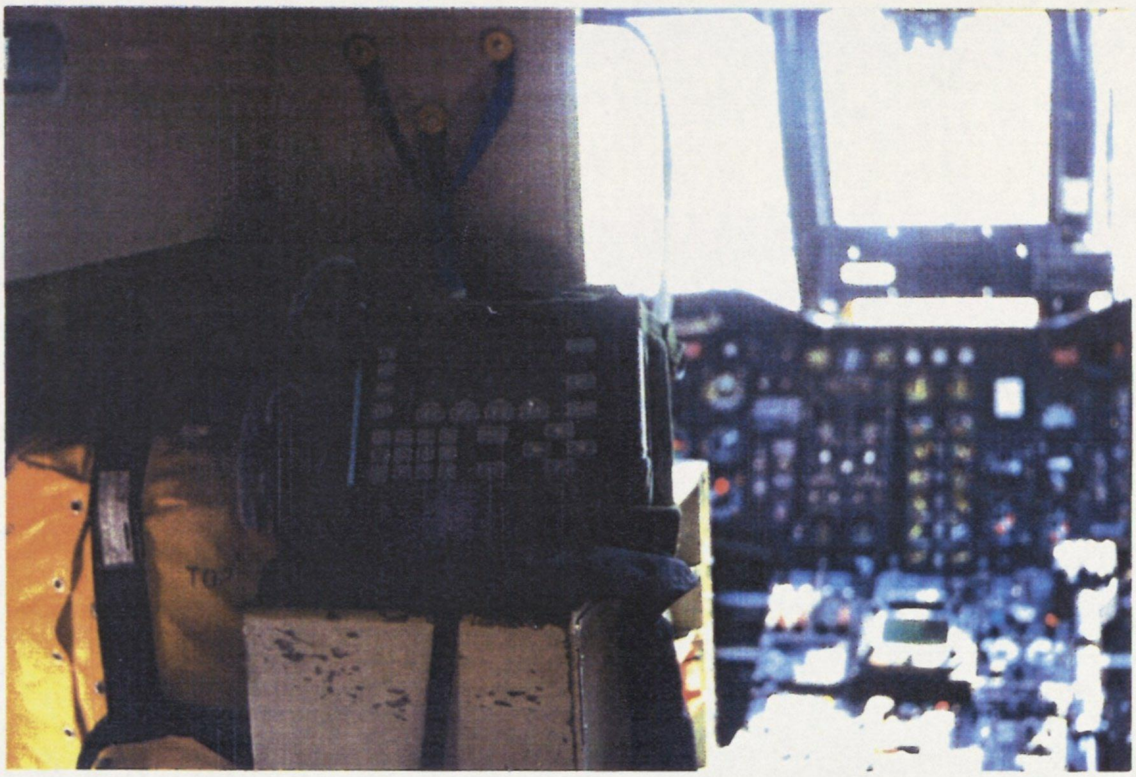


FIGURE 3.4

TOP: DRU on aircraft

BOTTOM: DRU and GSC

EXTERNAL TRANSMISSION MULTIPLEXER (ETMX)

MAIN PROCESSOR UNIT (MPU)

EXTERNAL ENGINE MULTIPLEXER (EEMX)

PILOT CONTROLLED INTERFACE (PCI)

FIGURE 3.5 : Airborne system components

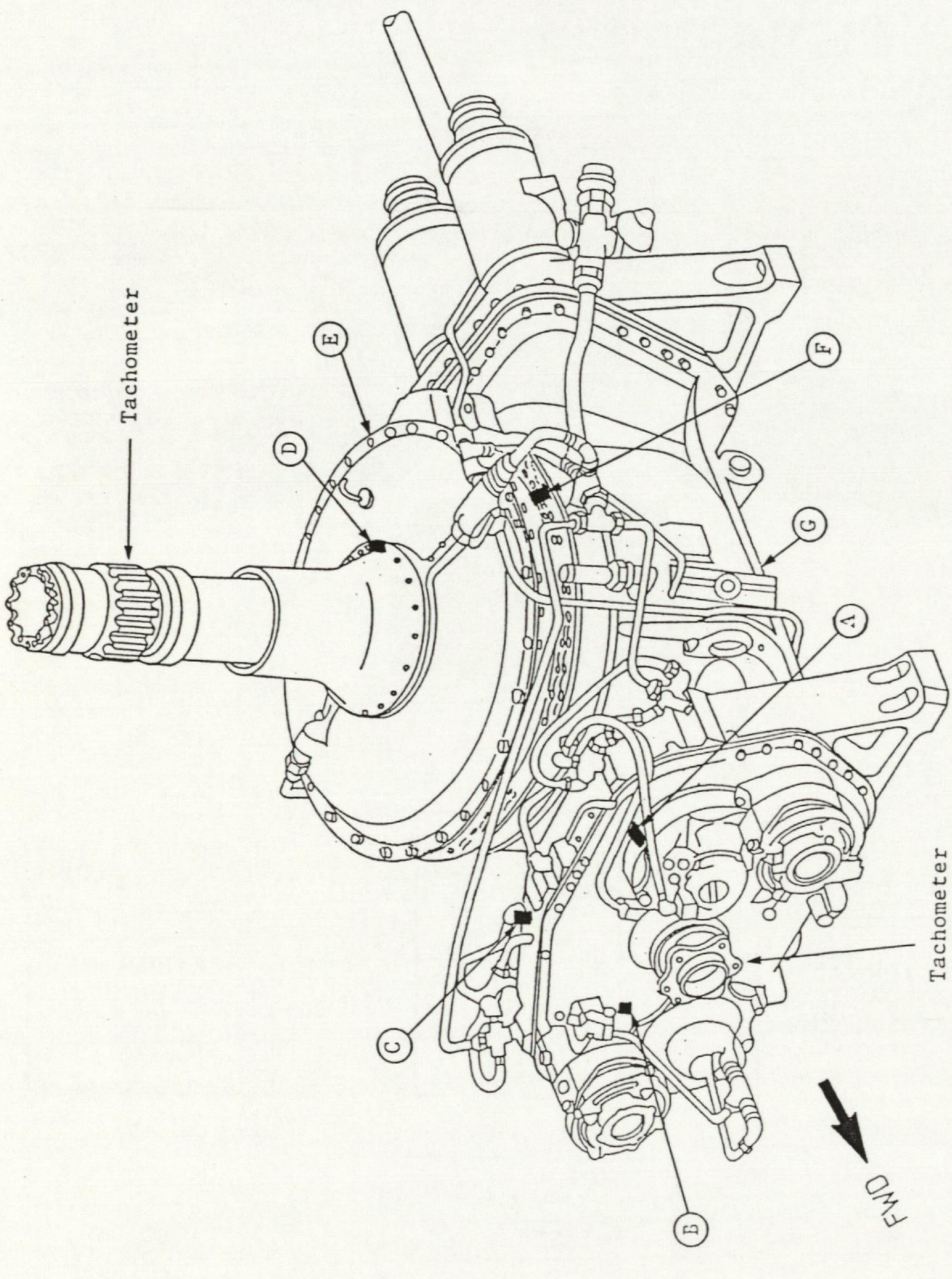


FIGURE 3.6 : S61 main gearbox sensor locations

4.0 HUM SYSTEM FUNCTIONAL DESCRIPTION

This section describes the functions and operating modes of the airborne and ground based systems.

4.1 Airborne system

Item 4.1.1 describes the airborne system operating modes. As has been explained previously, the airborne system is logically partitioned into two sub-systems; (i) the transmission and rotor vibration monitoring sub-system, and (ii) the engine monitoring and data management sub-system. Items 4.1.2 and 4.1.3 present separate functional descriptions of these two sub-systems.

4.1.1 *Airborne system operating modes*

The MPU performs a series of functions, carrying out a number of different analyses and transferring data to and from the DRU. In order to identify when different functions should be performed the HUMS was designed to identify a number of different operating states known as modes. These modes are listed below and are illustrated in the operating modes transition diagram shown in Figure 4.1.

(1) **Power-Up Self Test (PUST)**

This mode is entered automatically on power up. Each of the separate modules performs a self test function, which is then reported back to the DMC. The self test includes the EEMX and ETMX.

(2) **Restricted Ground Crew Access (RGCA)**

The system enters this mode if it detects a failure during PUST.

(3) **Ground Crew Access (GCA)**

The system enters this mode if all modules pass their self test. Within this mode the ground crew can transfer configuration data into the system, or download results to the DRU. Using the DRU the ground crew can also request that the system enters Analogue Verification mode.

(4) **Normal Operation (NO)**

This mode is entered automatically when the DMC module detects that the engines have started. In this mode the sub-systems perform their various analysis functions, the pilot can also initiate certain analyses via the PCI. Using the DRU, the operator can request that the system enters Analogue Verification mode. The system automatically returns to GCA mode on engine shut-down.

(5) **Analogue Verification (AV)**

This mode allows an operator to use the DRU to direct a selected accelerometer or tachometer signal to a test point for tape recording or display on an oscilloscope. In addition the operator can request that a particular analysis is performed, with the results returned to the DRU for display.

4.1.2 *Transmission and rotor vibration monitoring sub-system*

The sub-system consists of three elements:

(i) The Transputer Processor Card (TPC), which performs control and analysis functions.

(ii) The Vibration Data Acquisition Card (VDAC), which performs the digital signal processing.

(iii) The External Transmission Multiplexer (ETMX), which performs the signal conditioning for the sensors.

The functions of the ETMX have been described in Section 3.2.2, the following sections give functional descriptions of the TPC and VDAC.

4.1.2.1 Transputer processor card

(1) **Power-Up Self Test Mode (PUST)**

When in PUST the TPC performs a series of local tests and reports the result back to the DMC. If the TPC detects a failure it automatically enters RGCA mode, otherwise the system waits for the DMC to inform it to enter GCA mode.

(2) **Ground Crew Access Mode (RGCA/GCA)**

When in RGCA or GCA mode, an operator can request that configuration data is transferred to the TPC for storage. This configuration data is transferred from the DRU via the DMC. The TPC configuration data contains details of the analysis schedule, the parameters defining each analysis, the sensors required for each analysis, and information on sensors and ETMX channel allocations.

(3) **Normal Operation mode (NO)**

Within the NO mode the TPC schedules the analyses which are defined in the configuration data and returns the analysis results to the DMC for storage. However the analyses performed are dependent upon the aircraft operating regime. The TPC is informed by the DMC of the state of the weight on wheels switch, the current combined engine torque, and whether the pilot has issued a request through the PCI. These inputs are used to determine the following flight regimes in which different analyses may be scheduled:

- Ground
- Cruise
- PCI ground (ground option on PCI selected)
- PCI 70 knots (70 knots option on PCI selected)
- PCI 110 knots (110 knots option on PCI selected)
- Unknown (defined as any other flight condition)

Once the flight regime has been identified the TPC schedules appropriate analyses, using it's configuration data to define which analyses will be performed and the order of the analyses.

The transmission vibration analysis function is performed only in the cruise regime under steady torque conditions. When the system is in a regime where vibration analysis can be performed it carries out the following steps:

(a) The TPC reads the schedule associated with the current regime and identifies the next analysis to be run.

(b) The TPC requests the current aircraft time and flight conditions from the DMC, and checks that the flight conditions are correct for the selected analysis.

(c) The TPC identifies the parameters which define the sensors and analysis stages for this analysis. It then issues requests to: (i) the ETMX to select the appropriate accelerometer and tachometer channels; and (ii) the VDAC to set up the analogue path and the required digital signal processing option for the analysis.

(d) Digitised vibration data is transmitted from the VDAC and analysed by the TPC. If the analysis is Rotor Track and Balance (RT&B), tracker timing data is transferred from the VDAC.

(e) The analysis results are transferred to the DMC, along with the aircraft time and aircraft flight parameters.

(f) The TPC informs the DMC of the conclusion of the analysis, if a sensor failure was recorded it transmits to the DMC a sensor failure message. The schedule is incremented to the next analysis.

The transmission vibration analysis schedule set up for the S61N during the trial contains 19 analyses:

Main gearbox combiner shaft
Main gearbox stbd freewheel
Main gearbox port freewheel
Main gearbox eng 2 input
Main gearbox eng 1 input
Main gearbox main bevel
Main gearbox tail take off
Main gearbox epicyclic sun
Main gearbox epicyclic planet
Main gearbox epicyclic ann
Intermediate gearbox input/output shafts
Tail gearbox input shaft
Tail gearbox output shaft
Main gearbox eng 1 input
Main gearbox eng 2 input
Main gearbox port freewheel
Main gearbox stbd freewheel
Main Rotor Balance
Tail Rotor Balance

The schedule is run continuously when the aircraft is in a cruise condition. A single schedule takes approximately 18 minutes to complete therefore, with the exception of the main gearbox input and freewheel shafts, each transmission component is monitored every 18 minutes. Improvements made to the production HUMS have further reduced this schedule cycle time. The main gearbox input and freewheel shafts are included twice in the schedule, so these components are analysed at twice the schedule cycle frequency.

Fatigue damage propagation rates depend on the rate of accumulation of fatigue cycles. For a gear or shaft a fatigue cycle is one revolution of the shaft, therefore the rate of accumulation of fatigue cycles is directly related to the rotational speed of the shaft. The monitoring interval should be related to the rate of damage propagation, therefore it is necessary to monitor high speed shafts more frequently than low speed shafts.

(4) **Analogue Verification mode (AV)**

In the AV mode the operator can control the operations of the vibration analysis sub-system. Using the DRU, the operator can request that the system routes accelerometer or tachometer signals to a buffered test point, or performs a particular analysis and displays the results on the DRU.

4.1.2.2 Vibration Data Acquisition Card (VDAC)

The VDAC performs the basic signal processing operations required within the system. These operations are performed under the request of the TPC and process signals selected by the ETMX.

In Normal Operation mode (NO) the VDAC carries out the following sequence of operations:

(a) On receipt of set-up messages from the TPC, the VDAC selects the requested accelerometer, tachometer and tracker channels, sets up the required DSP algorithm, and starts the sampling.

(b) When requested, the VDAC sends the digitised data to the TPC. If tracker data has been requested the system transfers the tracker timings to the TPC.

4.1.3 *Engine monitoring and data management sub-system*

The sub-system consists of two permanent on-board elements, with a third item used for system verification/evaluation purposes:

(i) A Data Management Card (DMC), which implements the engine monitoring algorithms and provides a data management and results storage function for the whole on-board system.

(ii) An External Engine Multiplexer (EEMX) which provides a stream of digitised validated engine and airframe parameter data to the DMC.

(iii) An Engine monitoring verification tape recorder which provides facilities for recording a reduced data rate version of the EEMX data together with the engine monitoring results data.

The DMC controls the initialisation of the whole on-board HUMS equipment and also provides engine/regime data to the vibration monitoring sub-system as necessary. The functionality of the DMC is described below.

4.1.3.1 Data management card

The DMC performs both the engine monitoring tasks and a range of additional functions which support the system-wide operation of the on-board equipment, including the vibration monitoring sub-system. The DMC also determines which of the primary modes the system should be operating in. The DMC functions are briefly described below.

(1) **Power-Up Self Test mode (PUST)**

The DMC controls the master reset signal for itself, the VDAC and the TPC. On power-up the DMC releases the reset line and each card performs its own PUST independently.

(2) **System mode and regime control**

The DMC determines which mode the system is operating in (based on the status of the various inputs) and passes appropriate messages to the other modules within the airborne system.

In Normal Operating Mode (NO) the DMC provides all normal engine monitoring and data management functions for the system.

(3) **Engine monitoring functions**

These are described in Section 2.3 of this report.

(4) **Manual flight regime selection (PCI initiated)**

The PCI provides discrete inputs to the system to initiate power assurance checks and inform the system of the operating regime for rotor track and balance and engine vibration analysis.

The operating regimes are as follows:

(i) Ground
(ii) Cruise 70 knots
(iii) Cruise 110 knots
(iv) PAC-1
(v) PAC-2

Regimes (i), (ii) and (iii) are for rotor track and balance functions and require this information to be passed to the TPC and VDAC. Regimes (iv) and (v) are for Power Assurance or Topping checks and are DMC specific.

Validity checks are performed to determine that the regime selected is compatible with the current state of the engine/airframe inputs, eg. the PCI 'ground' regime is only accepted if the Weight-on-Wheels input is 'true'.

(5) **Vibration sub-system result recording and exceedance detection**

Each time the TPC completes a vibration analysis the results data is sent to the DMC for storage in non-volatile memory and exceedance detection. Exceedance detection is performed by comparing the results against pre-learnt threshold data which has been uploaded from the GSC.

The DMC stores the last 5 sets of indicator values for each analysis, plus the values of the last 75 indicators in exceedance. The following additional data is stored with each result: airspeed, altitude, OAT, combined engine torque, and time of occurrence.

Similar data is stored for the rotor track and balance results.

(6) **Chip detection alarms**

Whenever a chip is detected in one of the three gearboxes monitored, a message is received from the ETMX to log this occurrence with the flight time.

(7) **Data management and storage**

Data is formatted and recorded in non-volatile memory for subsequent retrieval by the DRU.

(8) **Data inputs**

Data is input to the system via two methods, by discrete inputs directly into the MPU and by data transferred via the communication interfaces to the ETMX and EEMX.

4.2 Ground based equipment

4.2.1 *Data Retrieval Unit (DRU)*

The DRU is the main interface between the flight line and the HUMS and is shown in Figure 4.2. To simplify the interface to the operator, the DRU is programmed within its own language to present to the operator a hierarchy of menus and forms for data input, a menu is shown in Figure 4.3. Display from the unit is achieved through using standard graphic displays and text. Displays may be updated by use of the cursor keys, numerical information can be entered using the numerical keys.

All of the operations performed by the DRU are menu driven. The options selectable from the DRU can be configured into two sets, both or either of which may be password protected to prevent unauthorised use. The two categories of access are referred to as:

1 Ground support personnel
2 Maintenance personnel

The operations which can be performed by the ground support personnel can also be performed by the maintenance personnel, but not vice versa. The DRU performs the following operations:

1 Transfer of data between the MPU and the GSC via the DRU

2 Display of the MPU analysis results

3 Control and collection of verification data

4 Set up and configuration of the airborne system

5 Set up of users and passwords for the DRU

4.2.1.1 DRU data transfer

The data transfer option on the DRU performs two functions: The transfer of all analysis results produced within the MPU to the GSC, and the block transfer of the analysis configuration set up within GSC to the MPU. Result transfer is available at ground support level, whilst configuration transfer is restricted to maintenance level. Data transfer can be performed by the DRU whenever the airborne system is in Ground Crew Access mode.

The last 5 indicator values for each analysis plus additional values of any indicators exceeding thresholds are transferred from the DMC. The choice of 5 indicator values was made as this provides sufficient data to identify trends occurring within a flight, but does not fill up the groundstation database unnecessarily. The DRU maintains within its internal non-volatile memory the last five sets of analysis results downloaded from the MPU. To transfer results to the GSC the operator connects the DRU to the GSC and requests that results for a particular aircraft are transferred.

To transfer configuration data to the airborne system the operator first connects the DRU to the GSC, and then requests that the GSC transfer the configuration for a particular aircraft. On completion of transfer the DRU is used to load this data into the MPU.

4.2.1.2 Results display

The DRU will allow an operator to display a selected portion of the analysis results from the last download for each aircraft. Although all analysis results are available for display, only a summary of the results is displayed to the operator. The contents of the results summary was selected in conjunction with BIHL, as information upon which the ground support personnel can act. In particular this information contains the state of all on-board alarms, whether produced by the monitoring functions or by system self test.

The information selected for display on the DRU included:

- Power assurance results
- Topping results
- Engine limit exceedances
- Oil temperature exceedances
- Aircraft usage statistics
- Gearbox vibration exceedances
- Chip detector status
- Main rotor balance exceedances
- Main rotor track and balance data
- Tail rotor balance exceedances
- Sensor failures
- System self-test failures

4.2.1.3 Analogue verification

The AV mode of the MPU is selected and controlled by the DRU, this option is restricted by password to maintenance level. When the operator has selected AV mode, accelerometer and tachometer signals may be selected, and routed to a test point for oscilloscope observation or recording. The system can also be commanded to perform a particular analysis.

4.2.1.4 Configuring the airborne system

In addition to the configuration transfer described in Section 4.2.1.1, the DRU is used to enter other configuration data into the airborne system. This option is restricted by password to maintenance level.

The following operations can be performed using the DRU:

- Setting of the MPU real time clock.
- Programming of the external multiplexers with the aircraft registration
- Reading and clearing of MPU fault flags
- Requesting that the MPU performs a system reset

4.2.1.5 Password setup

This allows an operator to modify the named users permitted to log into the DRU. This function is restricted to maintenance level. The operator can enter, modify, or remove named users.

4.2.2 *Ground Station Computer (GSC)*

The Ground Station Computer (GSC) is designed to allow operators to:

1 Set up the configuration of the airborne system
2 View the results from the aircraft

To interrogate the database the operator uses a series of graphical diagrams, known as mimics, that represent the aircraft being monitored. By selecting parts of mimics using a mouse, the operator can request more detailed information about different parts of the database. The top level mimic is a set of aircraft identified by registration, Figure 4.4. By selecting one of the aircraft with the mouse, the next level of the database is displayed, Figure 4.5.

Alarms within the system are indicated by parts of the mimic diagram flashing. The severity of the alarm is indicated by the colour of the component that is flashing. Within any one level of a mimic any alarms that occur at a lower level mimic are propagated to the higher diagram. This means that if, for example, an exceedance has been recorded for a gear within the main gearbox on Figure 4.5, then when the top level mimic (Figure 4.4) is viewed, the symbol representing the particular aircraft will indicate, by flashing in the appropriate colour, the alarm state detected.

The GSC performs the following functions:

(1) Configuration of the on-board analysis. This is based upon data input by the user, and data produced by the airborne system.

(2) Storage and display of the results of the analysis.

(3) Storage and display of other maintenance information. The GSC was configured to not only record the airborne information, but also to allow for the inclusion of aircraft health and usage data produced by existing maintenance systems within BIHL, for example the oil analysis programme carried out in conjunction with the HUM trial.

4.2.2.1 Configuring of on-board analysis

The configuration data that is loaded into the MPU for controlling the analysis is derived from three separate sources within the GSC:

1 **Component description information**

This is data describing the mechanical configuration, limits, and other information on the separate components that are to be analysed by the MPU. Most of this information cannot be altered by operators and is entered when the GSC database is configured by SHL. The component description information covers the following data about the aircraft:

- Exceedance limits.
- Physical details of the rotors and gearboxes.

- Parameters for of each of the transmission vibration analyses.
- Description of aircraft engine and gearbox types.
- Sensor channel assignments.
- HUMS component serial numbers and software release version numbers.

2 **Operator analysis parameters**

These parameters may be altered by the GSC operator to configure tests, or to initialise data. The operator analysis parameter information covers the following data about the system:

- Analysis schedule for each flight regime.
- Serial numbers of each of the maintainable units within the aircraft.
- Sensor calibration values.
- Usage data for each maintainable unit.
- Chip count resetting.
- Engine guard status (ice or FOD guard fitted).
- Password settings

3 **Airborne system parameters**

Data generated within the airborne system is also used within the configuration load. The airborne system parameters used in the configuration data include:

- Aircraft usage data (eg aircraft hours, low cycle fatigue counts, taxi time etc).
- Accumulative statistics of analysis results upon which the alarm thresholds are based.

The on-board gear and rotor analyses produce alarms within the airborne system by comparing results to pre-defined thresholds in the DMC. The thresholds are loaded into the system as part of the configuration data. These thresholds can either be produced automatically by the GSC, or be manually set by the operator. Automatic threshold setting is performed by calculating the statistical variation of the indicators over a number of flights. These thresholds only need to be re-learnt when there has been a change to the transmission system such as a gearbox replacement.

Configuration control is an important issue and is provided by a combination of the use of passwords and the automatic logging of configuration changes.

Maintainable units on the aircraft (ie engines and gearboxes) become time expired and require overhaul. The database therefore accommodates the removal of units from aircraft. Within the GSC a separate database was created, known as the stockpile. Using the configuration options, any maintainable unit on an aircraft could be transferred from an airframe to the stockpile and vice versa.

4.2.2.2 Result display

The results within the system are displayed through a series of mimics, organised in a hierarchy. The top level mimic, Figure 4.4, identifies the aircraft in the trial and includes a stockpile.

By selecting the next level of display the data associated with a particular aircraft is called up, Figure 4.5. In this display, icons are used to identify the major aircraft components (with associated monitoring data), records of all internal failures recorded by the system, aircraft usage data, and a summary of the analysis conclusions.

The usage display shows the duration of the last flight, and the accumulative total for the aircraft hours, taxiing time, rotor turning time, and the number of take offs.

By selecting one of the icons for the major aircraft components, displays of data associated with that component can be obtained. For example, by selecting one of the engine icons, various displays of engine data can be selected. Two examples are described - power assurance results and the power curve - as they illustrate different types of display.

The power assurance display is shown in Figure 4.6. This displays the values recorded by the airborne system for a particular aircraft hours and flight number. Values produced by the system can also be trended. The operator can scroll back through the database to examine previously recorded results, this historical position is shown on the trend by the solid vertical line.

The power curve display, Figure 4.7, is presented in the same format as the maintenance manual chart. The power curve data is manually recorded and entered into the GSC.

The main rotor display is shown in Figure 4.8. Results are shown in a tabular form, trended, and as a phase amplitude representation. The operator can select further displays to present rotor track data, or examine the adjustments made to the rotor head.

Figure 4.9 shows the mimic of the S61 main gearbox, selection of gear icons in this display gives the analysis results for each gear shaft. In addition, other gearbox related information can also be selected such as the accumulative chip and zapper counts, SOAP data, or the oil debris tribology analysis results.

Figure 4.10 shows all analysis results for the annulus gear in numerical and bar chart format. Four of the analysis indicators can also be trended to show the last 100 results. Selection of any bar chart will give a full size trend plot of all results for that indicator, multiple indicator trend plots can also be displayed.

The SOAP and tribology mimics are shown in Figures 4.11 and 4.12. These mimics display the analysis results in a similar format to the existing manual system. The operator can select any single element to obtain a complete trend plot of one of the indicators.

4.2.2.3 Entry of non-HUM produced data

Within the GSC provision is made for the operator to enter data that is not produced by the airborne HUMS, but which relates to the aircraft status. The operator may enter the following:

1 Tribology data. PQ Index values and data from the RPD analysis is manually entered into the database, where it is presented in the format shown in Figure 4.12. In the style of the SOAP displays, each type of wear particle has a bar indicator, defaulting to the last recorded value. Plots of particle quantity and PQ Index may be produced, preceding entries may be displayed by scrolling back in time on the displays.

2 SOAP data. This form allows the operator to enter the results of the Spectro oil analysis programme.

3 Stator vane scheduling. This form allows the operator to enter the current adjustment setting.

4 Tuning. This form allows the operator to enter the engine test results.

5 Power curve. This form allows the operator to enter the engine test results.

6 Power assurance. This form allows the operator to enter the pilot recorded PAC parameters.

7 Topping. This form allows the operator to enter the pilot recorded topping parameters.

8 Rotor adjustments. This option allows the operator to enter the rotor adjustments, for hub-weight, tabs, or pitch links.

4.2.2.4 SOAP database

A separate SOAP database is installed on the trial GSC to record and display SOAP data for the S61 aircraft which are not involved in the HUMS trial, and consequently do not have records within the HUMS database.

Analysis data is supplied to BIHL in the form of a computer printout. It is then manually entered into the GSC database. Data for the trial aircraft is entered into both SOAP and HUMS databases, to enable the fleet SOAP database to be complete, and to assess the concept of having SOAP and HUMS data available on the same displays.

The database is designed to record gearbox SOAP history over a complete overhaul to overhaul cycle. Within the database, the gearbox is regarded as the principal item, with the aircraft in which it is currently installed serving only to locate it more readily from the line operators point of view.

Time Since Overhaul, (TSO) of the gearbox is the key to the database. The gearbox TSO at installation into the aircraft is entered into the database along with the serial number and airframe hours at installation. Manually entered SOAP data is tagged with aircraft flying hours at the time of sampling. The database uses the installation TSO to calculate the TSO at the point when each successive SOAP sample is taken. TSO and airframe hours are displayed concurrently on the GSC screens.

The opening screen of the SOAP database is shown as Figure 4.13. A gearbox for which an element has exceeded an alert level will flash in a colour which indicates the level of exceedance recorded. The alert levels used on the GSC are set by BIHL in consultation with Spectro Laboratories. Adjustments to the alert levels may be carried out at the GSC, under password protection.

The opening screen for an individual gearbox is shown as Figure 4.11. Each monitored element is represented by a bar indicator, displaying the last recorded value. Airframe hours and TSO at the sample date are displayed. Preceding entries may be viewed by scrolling back in time, trend plots of the elements can also be displayed.

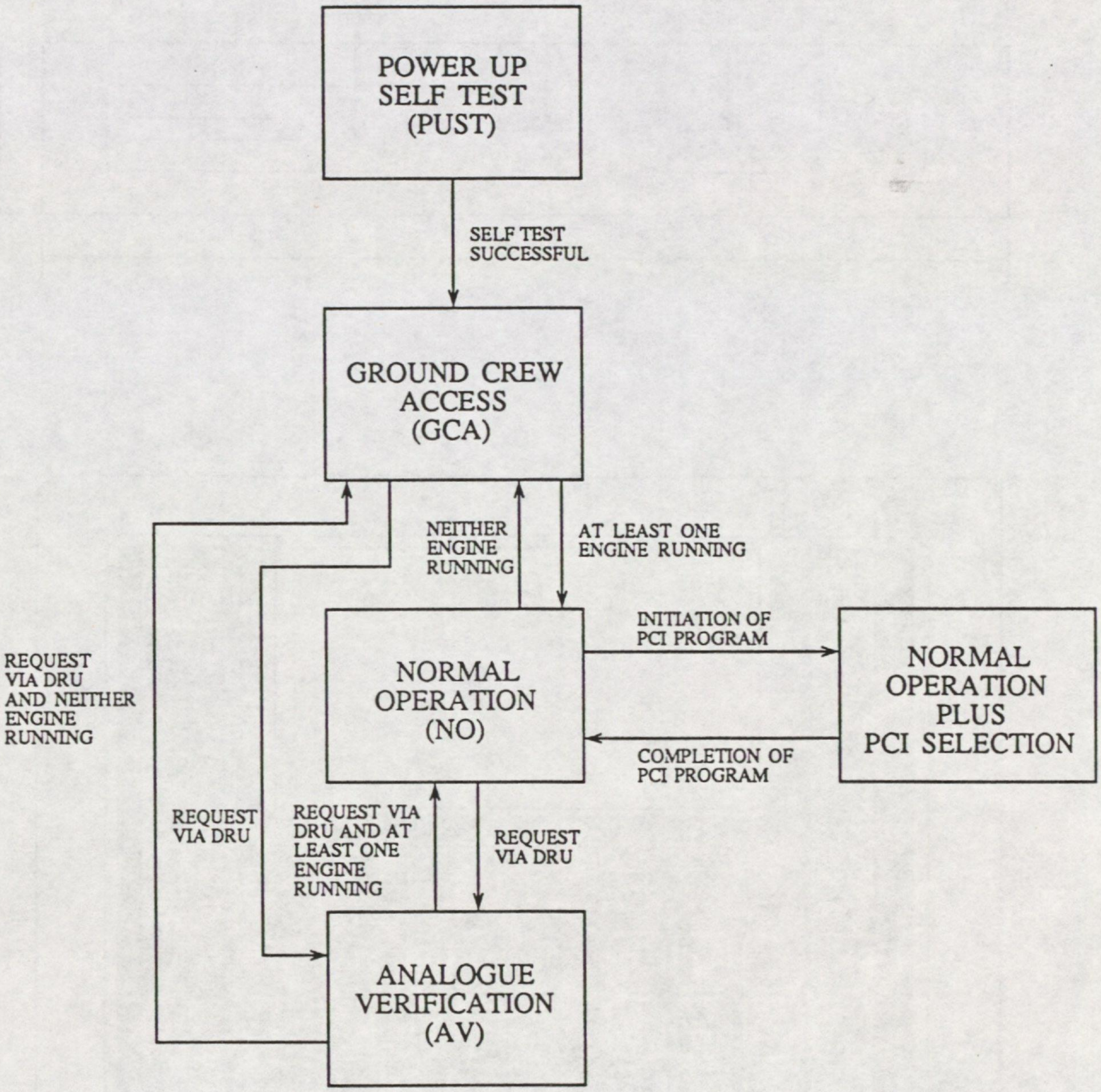
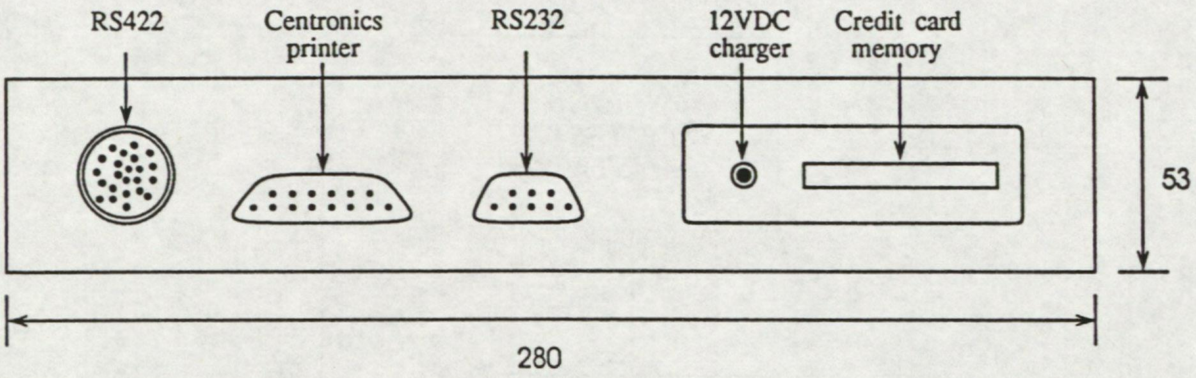


FIGURE 4.1 : Operating mode transition diagram



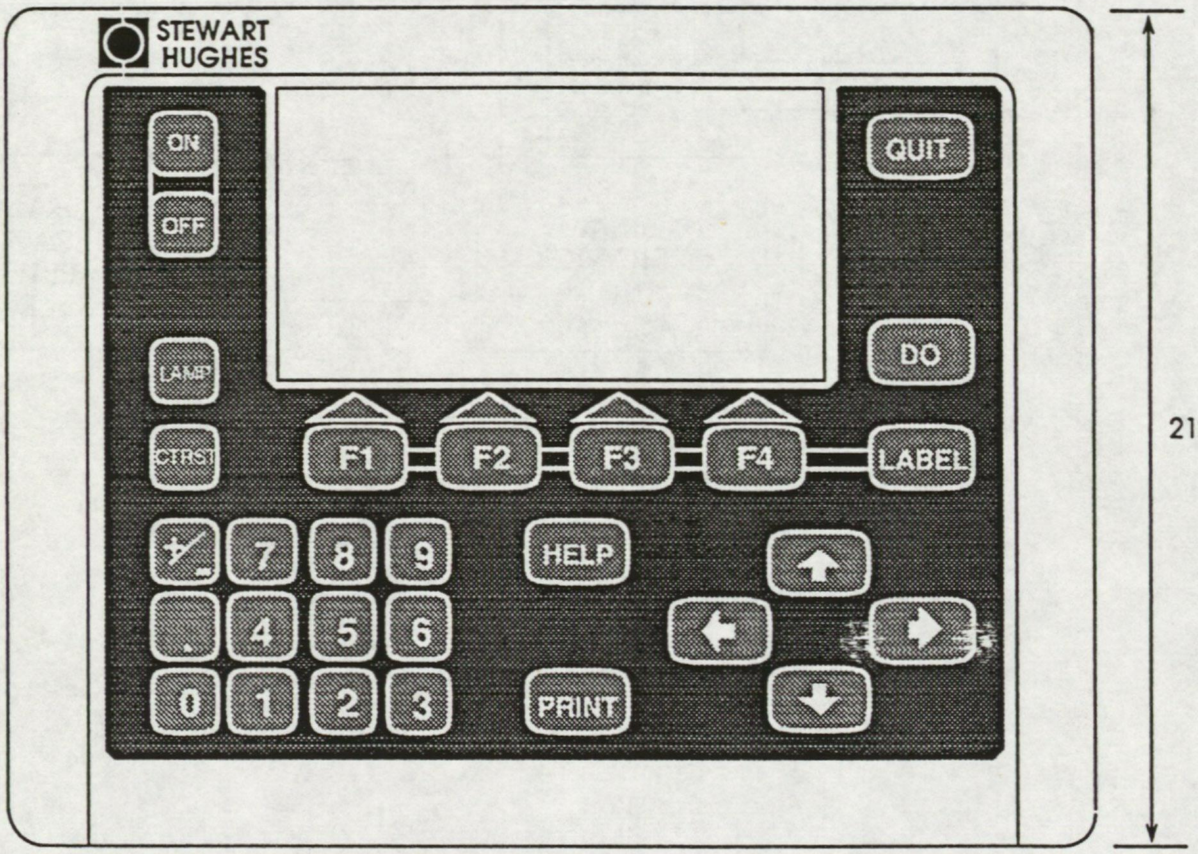


FIGURE 4.2 : Data Retrieval Unit (DRU)

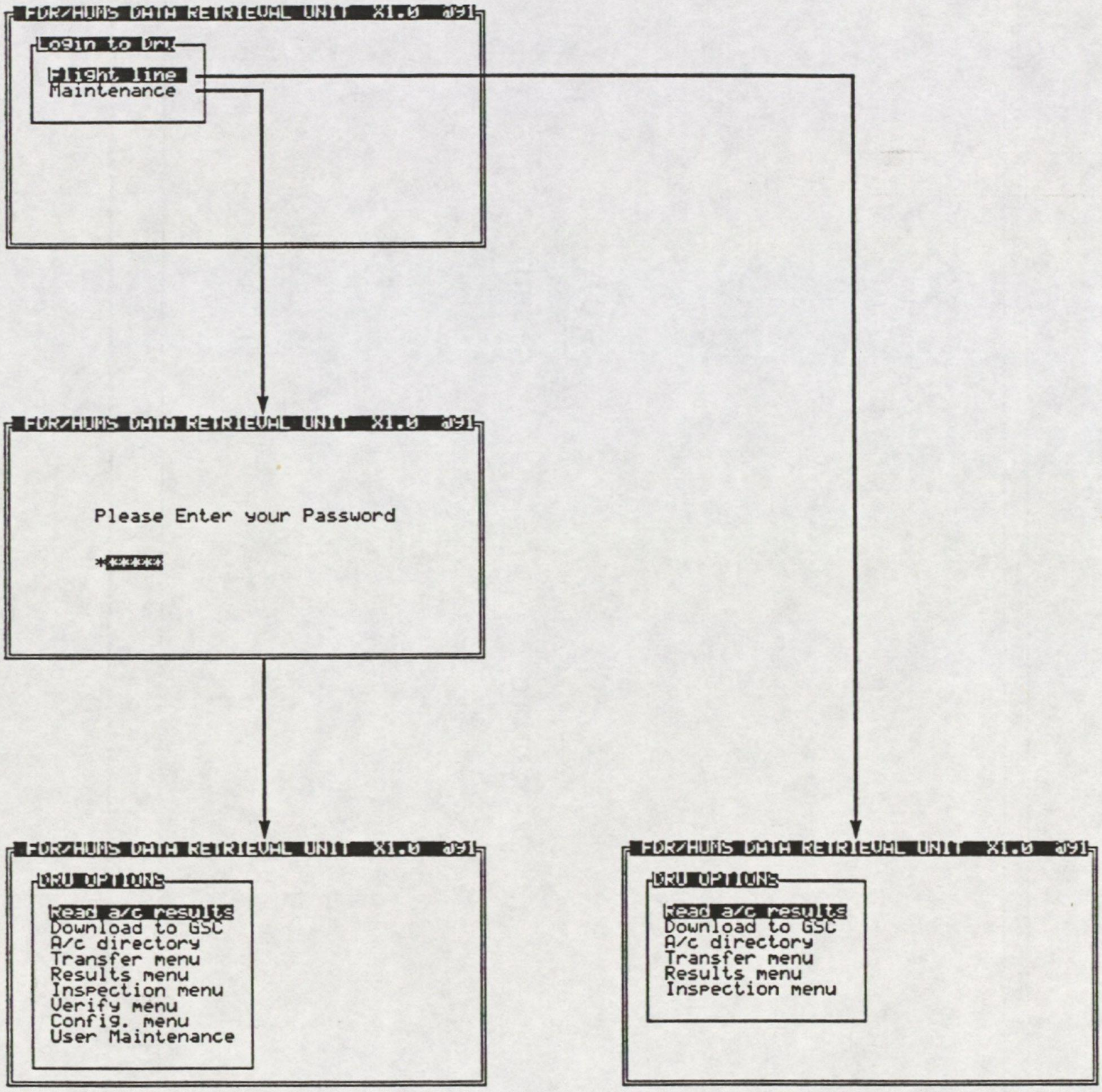


FIGURE 4.3 : DRU menu options

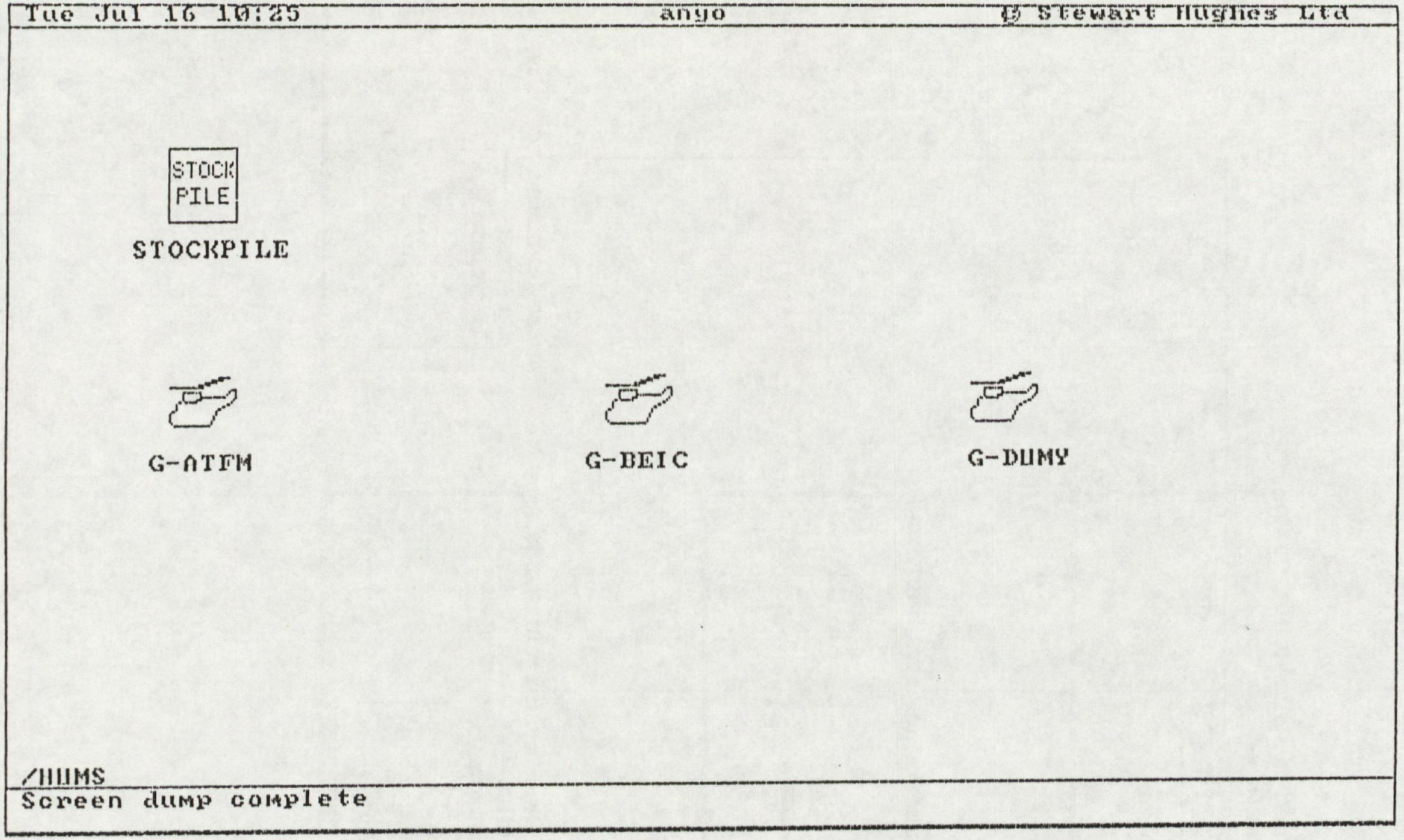


FIGURE 4.4 : HUMS top level mimic

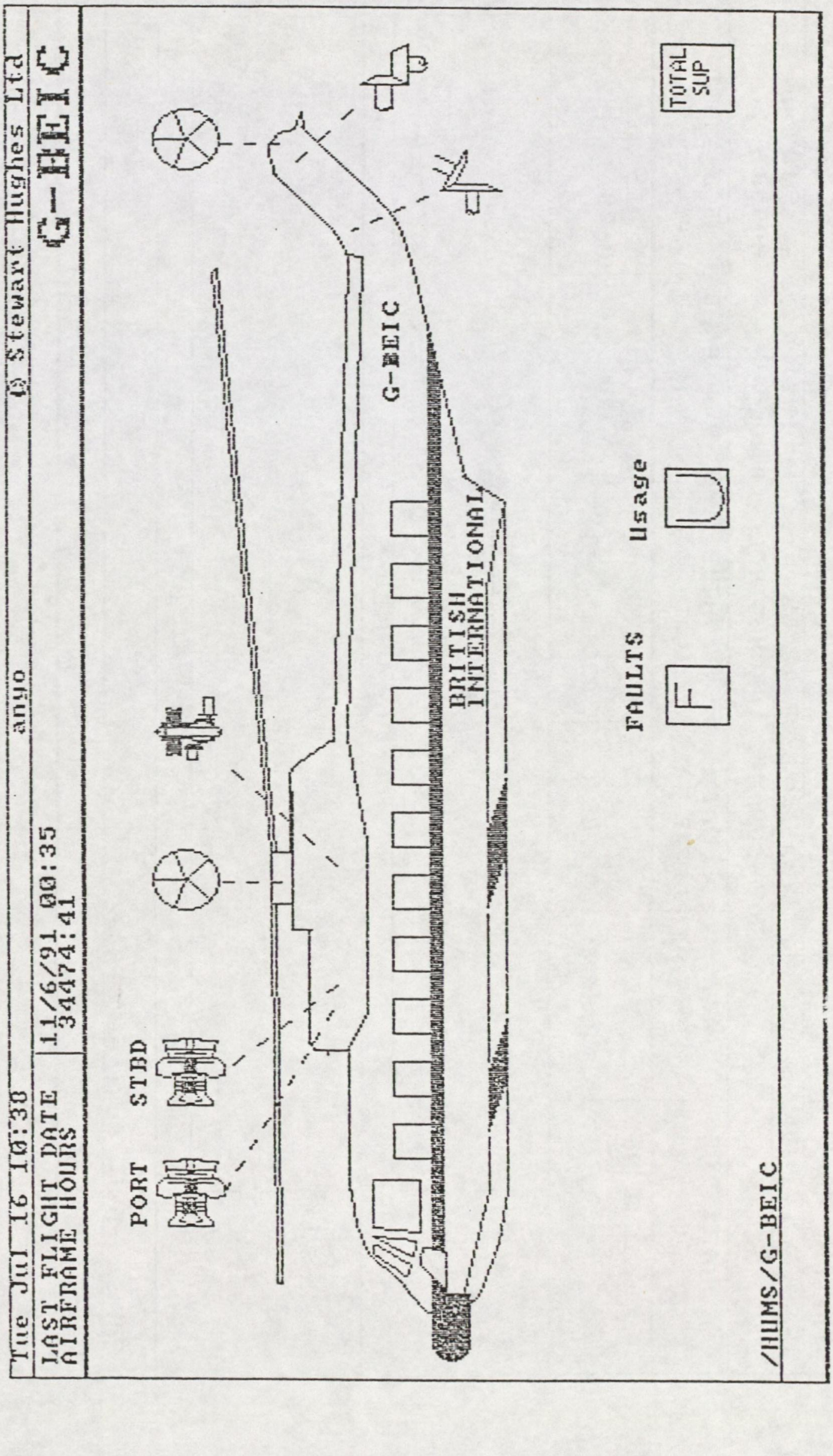


FIGURE 4.5 : Aircraft mimic

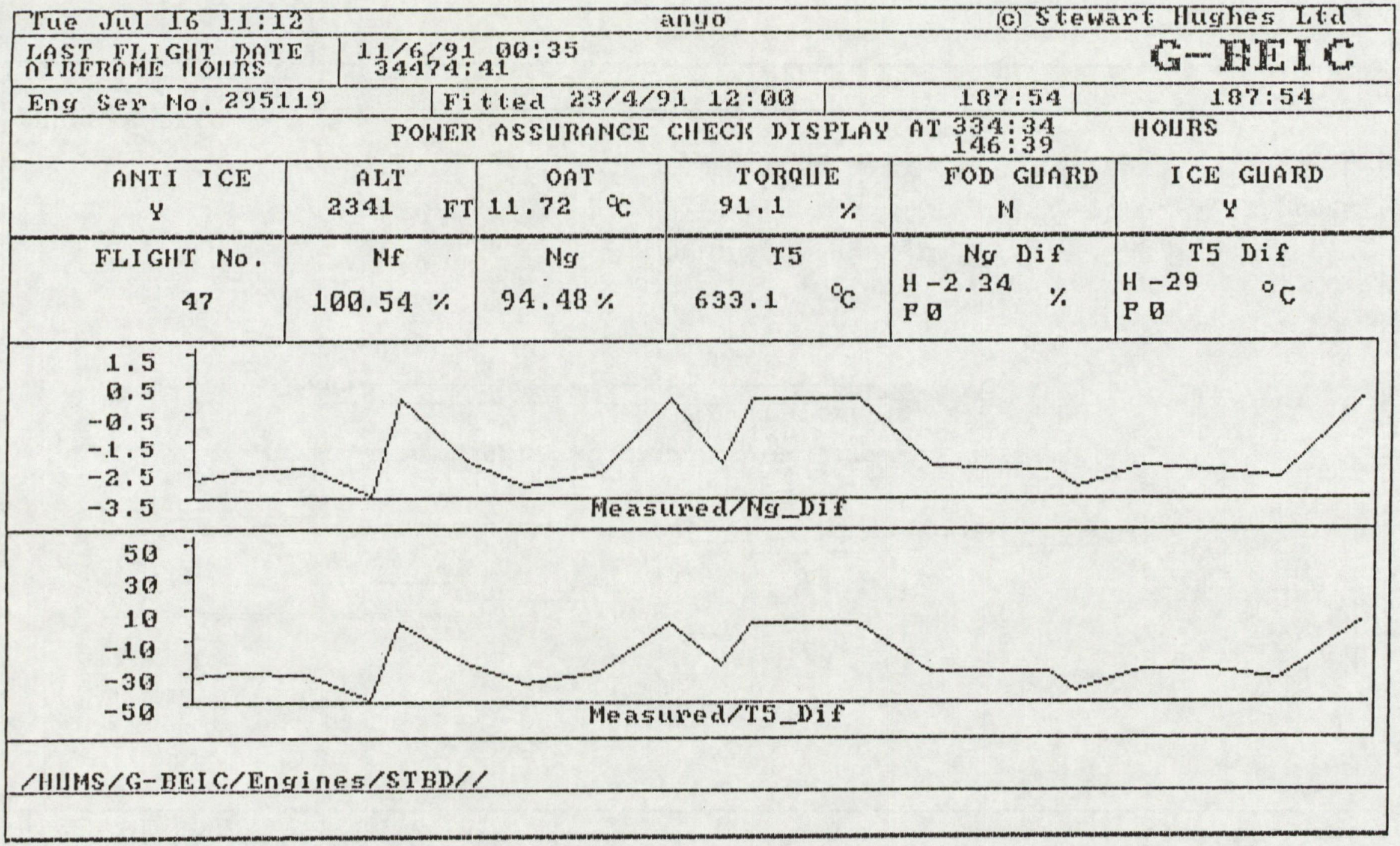


FIGURE 4.6 : Engine power assurance mimic

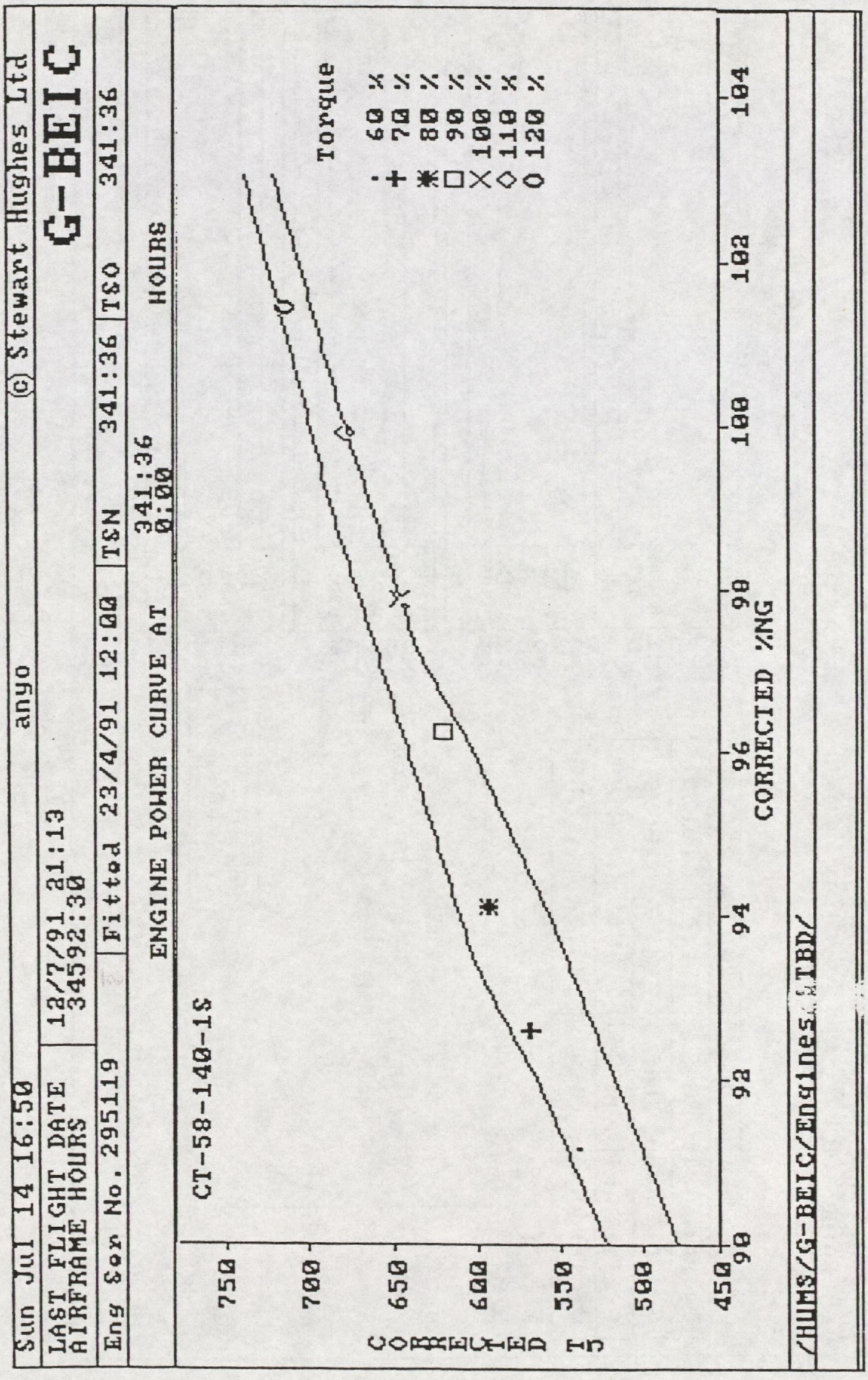


FIGURE 4.7 : Engine power curve mimic

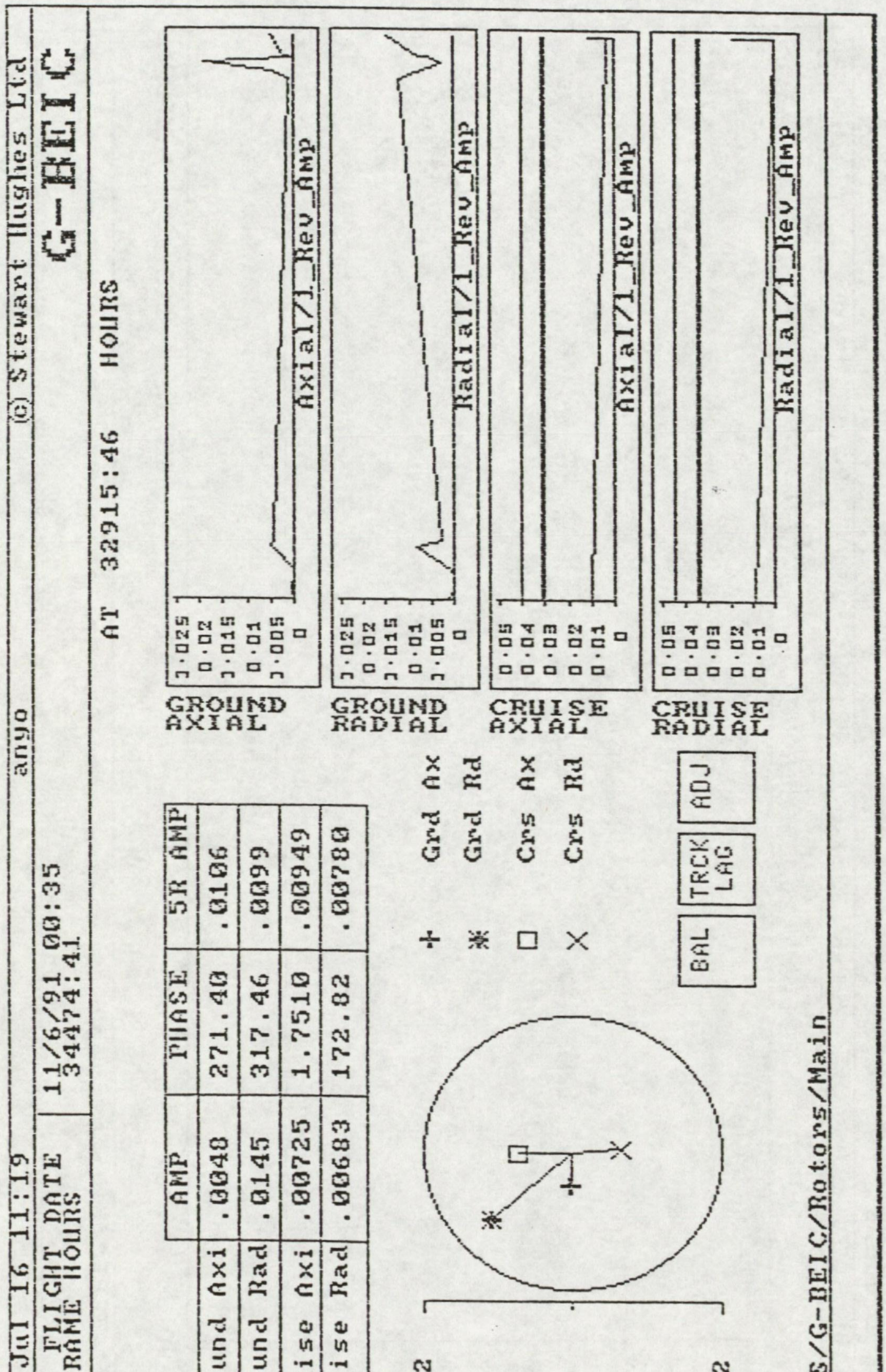


FIGURE 4.8 : Main rotor mimic

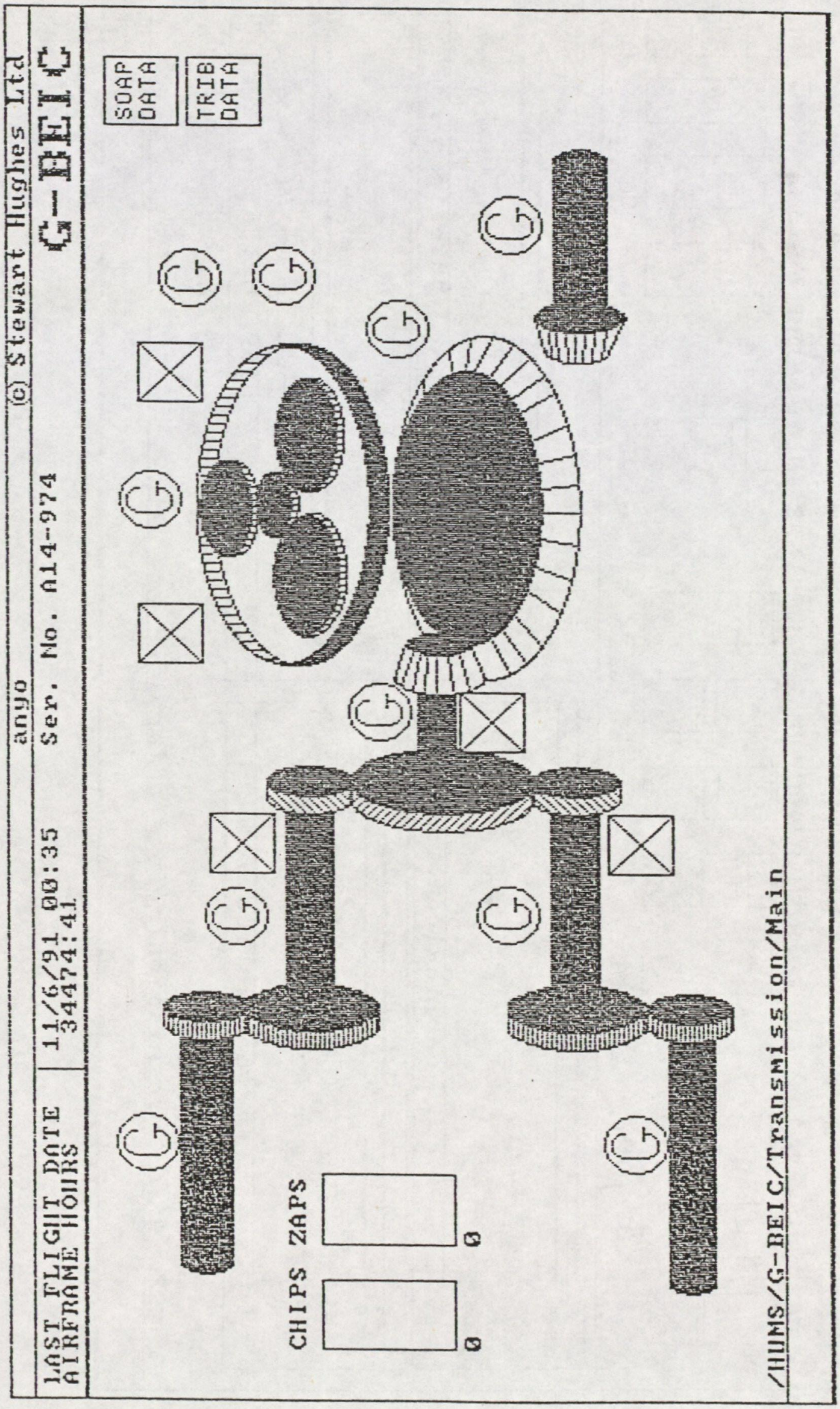


FIGURE 4.9 : Main gearbox mimic

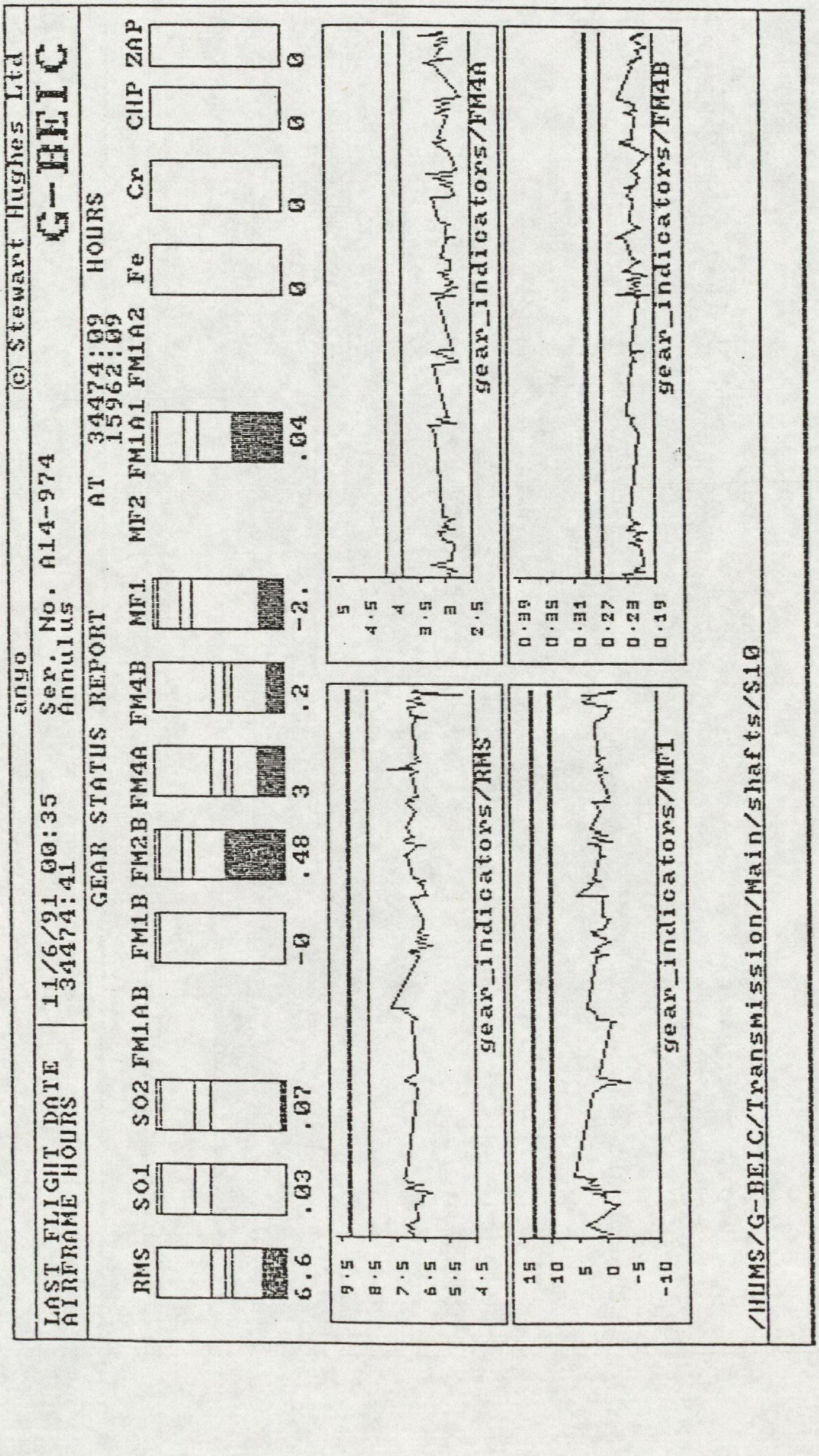


FIGURE 4.10 : Mimic for annulus gear

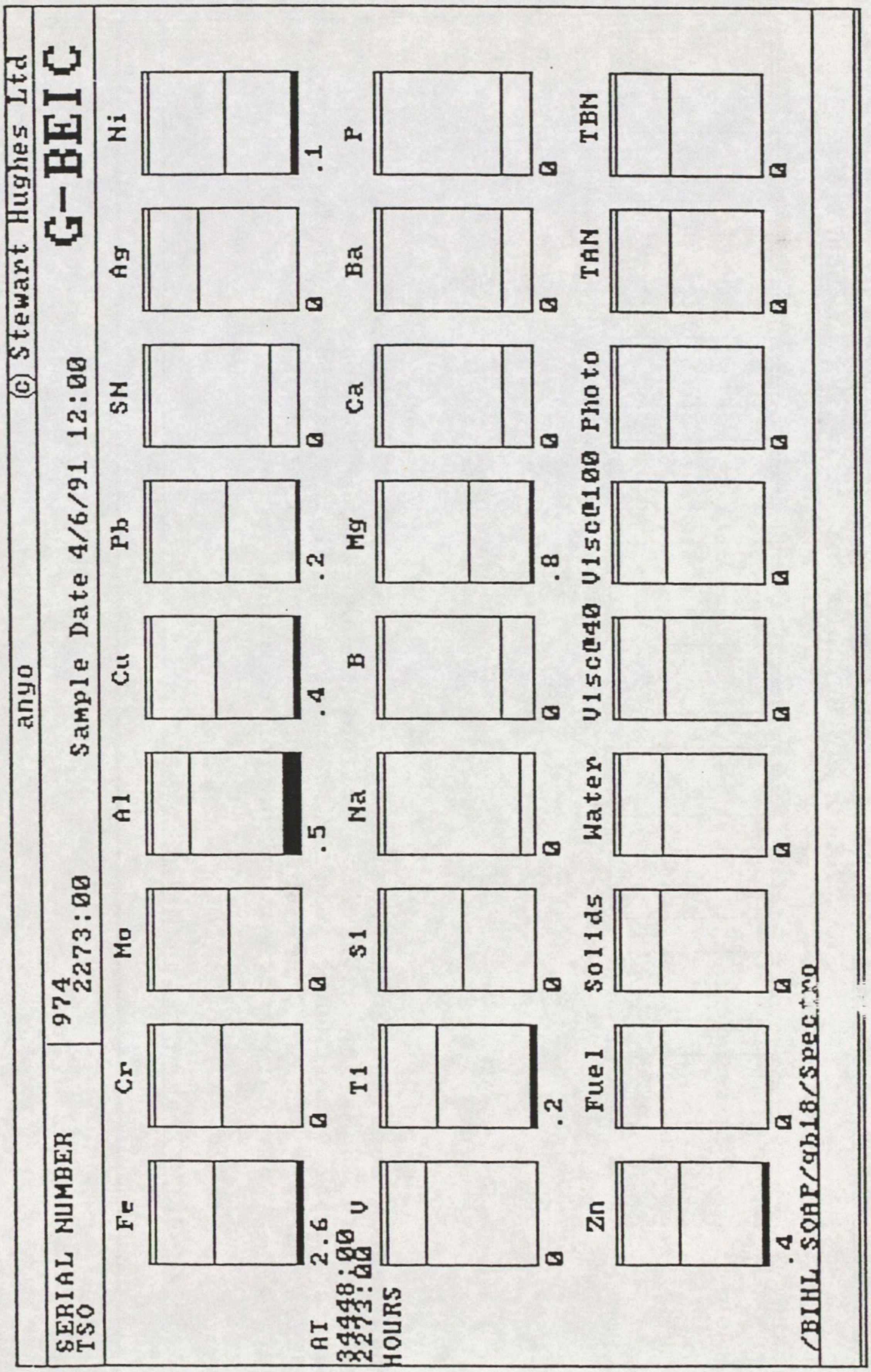


FIGURE 4.11 : Gearbox SOAP mimic

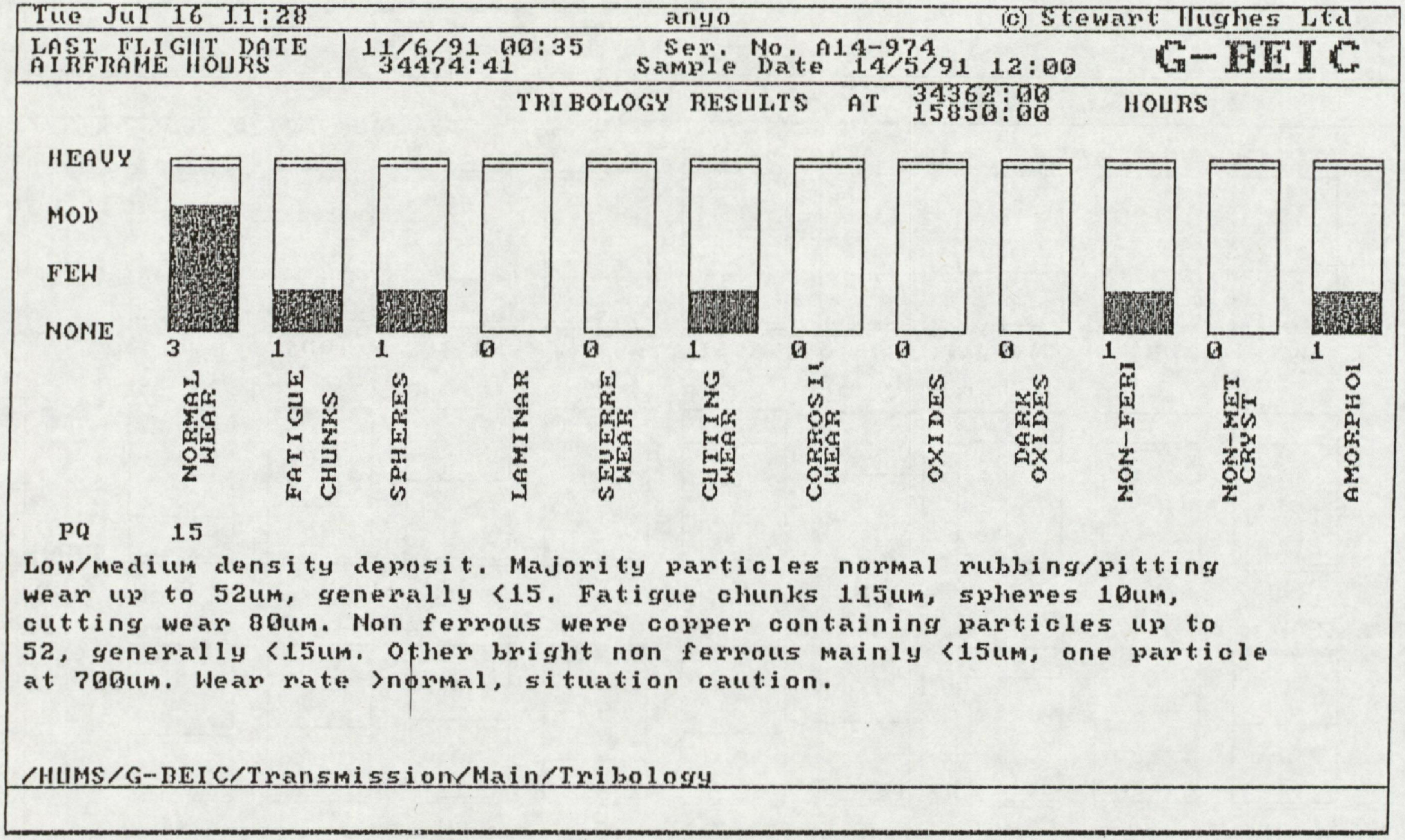


FIGURE 4.12 : Tribology mimic

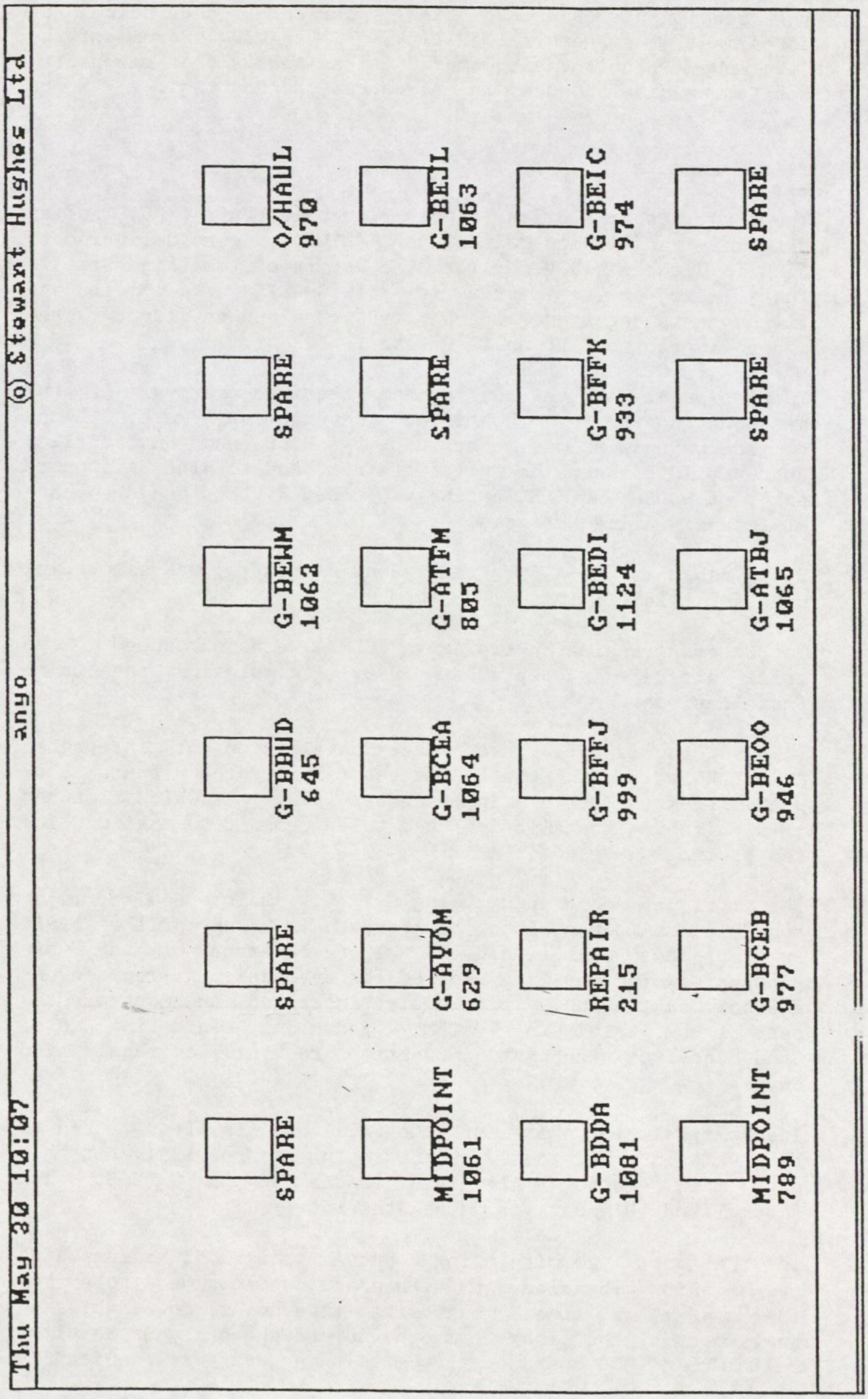


FIGURE 4.13 : SOAP database top level mimic

5.0 TRIAL EXPERIENCE

This section discusses the trial experience, and includes an assessment of system reliability, a review of some of the development problems encountered and an analysis of the health monitoring data produced in the course of the trial.

5.1 Trial schedule

The first airborne units, a Main Processing Unit (MPU), and an External Transmission Multiplexer (ETMX), were delivered to BIHL in October 1989, for the start of the flight trial. Installation of the system in S61N G-BEIC was completed and flight tests began on 7 October 1989. The second flight system was delivered to BIHL on 23 October.

Initial problems with the system required removal of the airborne units for continued development work. Bench commissioning work was continued by HSDE and SHL until 7 February 1990, when the units were returned to BIHL. A support party of HSDE and SHL engineers joined BIHL to begin a phase of intensive flight trials.

By 19 February, G-ATFM, the second aircraft, was also being used for trial flying.

The External Engine Multiplexers (EEMX) were introduced to the trial aircraft in September 1990, completing the trial installations.

Planning considerations for the installation of integrated HUMS/FDR systems in the BIHL fleet required the withdrawal of G-ATFM from the trial in December 1990, at which time the trial airborne installation had to be removed to make way for the production system.

The trial was continued using G-BEIC, which required major scheduled maintenance work at Aberdeen in March-April of 1991. Part of this work included the replacement of the main gearbox, which was time expired for overhaul. The replacement gearbox was the unit previously installed and monitored as part of the trial in G-ATFM, enabling monitoring to be conducted from mid-point inspection to full overhaul life completion.

The commissioning phase of the trial was finally declared to be have been completed by the beginning of June 1991. At this date main gearbox A14-974, installed in G-BEIC, had accumulated 107 hours of data gathering.

In the post commissioning phase the HUMS accumulated transmission vibration data with no adjustments made to either the system or the monitoring thresholds to enable an assessment of the long term behavior of the analysis results. A minimum of 300 hours post commissioning data was required by the CAA in order to draw realistic conclusions, this milestone was passed in late August 1991.

After completion of the formal, CAA sponsored phase of the trial, BIHL continued to operate the trial system to collect further data and gain as much value as possible from the trial installation. The trial system continued in operation until 6 December, at which time gearbox A14-974 became time expired for overhaul and was removed. The trial processing units were removed at this time.

The following table summarises the aircraft hours accumulated during the trial.

Gearbox Serial Number	Aircraft	Hours Flown
Pre-commissioning phase		
A14-1037	G-ATFM	507
A14-970	G-BEIC	488
A14-974	G-ATFM	484
A14-974	G-BEIC	107
Post-commissioning phase		
A14-974	G-BEIC	678
	Total hours:	2264

5.2 **System reliability**

The trial system was intended to be a technology demonstrator and was not designed to a specific MTBF criterion. The total time flown by the system during the course of the trial is insufficient to assess the MTBF. However, once the commissioning phase of the trial had been completed, no failures were experienced within the avionic units. The areas where some problems were encountered were the accelerometer mounts, cable installations (notably the transmission break plug) and the rotor brake tachometer.

Reliability of the GSC proved to be high, the failures experienced during the trial were of one floppy disk drive, and occasional instances of processing cards in the computer base coming loose, caused during transit of the computer back and forth between Shetland and the mainland to meet operational requirements.

5.2.1 *Accelerometer mounts*

The accelerometers proved to be reliable, with no failures experienced. Some difficulties were experienced with the bonding of the stainless steel mount blocks, a few bonds failed early in the trial. Inadequate surface preparation was thought to be the problem, as the failures generally occurred soon after installation.

An alternative accelerometer mount with a larger 'footprint' was obtained. This item was used to replace the Endevco blocks where bonding failures occurred. The larger surface area produced a more positive bond and only one subsequent failure occurred.

5.2.2 *Cable installations*

Some problems were encountered with the transmission break connector for the accelerometer and tachometer wiring. This was found to be vulnerable to water and oil ingress, and to damage caused by servicing personnel working in the area, problems that have in the past affected many helicopter systems from time to time.

Once installed there was little which could be done to overcome this problem. The position of the plug was such that it could be exposed to accidental damage (mainly by heavy boots) during servicing operations, as well as to rain and skin wash water.

5.2.3 *Tachometer probes*

Two failures of the inductive rotor brake tachometer probe occurred during the trial. The tachometer is a critical part of the HUMS, unless a suitable backup signal is available failure of this component disables the whole of the transmission vibration analysis system.

The tachometer probe was mounted on a bracket attached to the input casing of the main gearbox. Both probe failures were caused by a break in the cable at the point at which it is attached to the probe. The probe is subject to high vibration and the small diameter cable is rigidly fixed in the probe using a hard potting compound. The constant flexing of the cable due to the probe vibration apparently caused it to fail in fatigue at this point.

5.2.4 *Solutions to problems encountered*

In the light of the difficulties experienced during the trial, bonding is not recommended for use as an accelerometer attachment method for future systems. Accelerometers should be bolted to purpose designed mount brackets installed at casing split lines, or threaded into existing tapped holes.

The problems encountered with the transmission break connector could be minimised at the design stage, when the possibility of accidental damage caused by personnel working in the proximity of connectors should be considered, with close attention given to connector positioning.

The tachometer probe failures experienced on the trial system could be prevented by improved support of the cable adjacent to the probe.

5.3 HUMS development problems

As a result of the high level of sophistication of the prototype HUM system, a number of development problems were encountered which delayed the ending of the system commissioning phase and commencement of routine on-board vibration monitoring functions. Overcoming these problems, however, has enabled valuable lessons to be learned and the experience has provided an essential input to the design of the production HUM system.

At the time of designing the architecture of the HUMS trial system it was recognised that although there were essentially two sub-systems within the overall system (vibration and engine monitoring sub-systems) there was a need for interaction and communication between these functions. To prevent duplication of functionality within the system (ie, to make a more integrated system) the functionality could not be completely partitioned according to the hardware modules used within the system. This resulted in a greater degree of interfacing and hence more difficulty in resolving development problems when they arose. Some of the key issues are discussed below in approximately chronological order.

Problems were encountered with periodic lock-up of the link between the TPC and VDAC. The communications link between the transputers on the TPC and VDAC became corrupted by 'noise' and effectively disabled the vibration monitoring part of the system, resulting in little data being produced on a flight where this had occurred. The problem was solved by a combination of a software and hardware modification.

A number of failures of the vibration primary analysis process were initially recorded by the system. A tachometer signal quality check in the primary analysis software repeatedly rejected the rotor brake tachometer signal. The check ensures that signal averages are not disrupted by a deterioration in the tachometer signal caused by vibration or movement of the tachometer probe or 'noise' corruption of the signal. A stiffening angle was added to the tachometer probe mounting bracket and subsequent analysis of tape recorded data showed that a good quality tachometer signal was being obtained. Some small adjustments were also made to the tachometer signal check, no further signal rejections occurred.

Once vibration results were being reliably produced by the HUMS, an analysis of these showed that there was an unacceptable variability present in the data. Data stability was improved after the removal of a small rounding error in the primary analysis software and tightening up of the control of the signal averaging process. Variations in the aircraft flight regime during data acquisition were found to be a significant cause of data variability. Until flight regime information was available, the HUMS commenced analysis 5 minutes after take-off and stopped analysis only when weight on wheels was detected during landing.

The HUMS was designed to be able to automatically schedule vibration analysis functions using flight regime parameters of indicated airspeed, altitude, and engine torque. The first two parameters originated from the Penny & Giles Air Data Unit, torque came from the existing torque synchro instrumentation. These signals were digitised by the EEMX and thence made available for use within the HUMS equipment.

Delays in the commissioning of these items meant that the testing of flight regime controlled vibration analysis was delayed. Once the regime parameters were available, the HUMS was first allowed to acquire data over all flight regimes, but with the results tagged with regime data. Subsequent analysis showed that good data stability could be obtained using selected regime parameters to control the scheduling of transmission vibration analysis. The automatic flight regime control was implemented and subsequent data was observed to have good stability.

When the modifications described above had been made the HUMS accumulated data during a 'learning' period and statistically based monitoring thresholds were calculated from this. The thresholds were uploaded to the MPU and routine transmission vibration monitoring commenced.

There were delays in the obtaining of certification to fit the Automatic Blade Tracker to the S-61 (mounted externally on the aircraft). Once approval had been given testing revealed that, although the HUMS appeared to be correctly scheduling main rotor balance analyses, results were either not being passed back or stored correctly. Attempts were made to investigate the problem, however at the end of the CAA sponsored part of the trial this was still not properly resolved. As a result, no main rotor track and balance data was produced by the trial HUMS. Owing to the nearness of completion the production HUMS it was decided that all efforts should be focussed on the production system as this would provide the best opportunity to gain rotor track and balance experience.

A Tedeco Zapper fuzz burner chip detector was installed in the main gearbox, connected directly to the ETMX, where chip and zapper discharge counts were recorded separately. Owing to certification delays the zapper control unit was not cleared for flight and installed in G-BEIC until August 1990. It was evident almost immediately that the zapper was recording spurious fuzz burn discharge counts. The Tedeco system had initially been designed for the Westland Sea King. An investigation showed that the S61 and Sea King installations were fundamentally different, the Sea King installation being more complex with a series of relays and warning lights which were not installed in the S61. The system had been designed to take into account the resistance in the circuitry of the relays, diodes, and lights. Without the these the system was sensitive to aircraft bus power fluctuations, which were interpreted as bridging of the chip detector, triggering a zapper discharge. Tedeco modified the zapper unit to incorporate a suitable resistance and diodes to simulate the original system. This modification proved successful in that spurious zapper counts were no longer recorded.

5.4 Operational acceptability of trial system

5.4.1 *Data and configuration transfers using the DRU*

As part of the trial, BIHL line engineers at Sumburgh were given instruction in operation of the DRU and GSC for routine data downloads and configuration transfers. They reported that operation of the system at user level was acceptably simple, and had few adverse comments regarding the functions they were performing.

Data downloads were taken both between flights with the aircraft on the flight line, and in the hangar at the end of the days flying. On the flight line it proved to be a simple procedure to connect the DRU and carry out the data download process as part of the turnround servicing.

In the early days of the trial, the DRU to MPU communications were unreliable, producing data and configuration transfer failures. This caused some operator frustration, with repeated attempts at data transfer being required on some occasions. As a result it was advisable to have ground power available for the operation to avoid excess battery power consumption.

During the course of the trial, modifications eliminated the data and configuration transfer failures. By October 1990, the data transfer process was very reliable and was completed in less than 2 minutes. Data and configuration transfers were then performed using aircraft battery power only.

As helicopters in North Sea operations are often placed into situations where external power is available only for engine start, and not during turnround servicings, it is a considerable operational asset to be able to carry out data transfer into the DRU from the aircraft system and read the results using aircraft battery power. Under such circumstances, particularly in a busy operational situation, the transfer of results must fit in with the operational essentials of performing the turnround inspection and preparing for the next flight. Having a short, simple process which can be performed to the stage of giving an immediate "fit for further flight" indication greatly enhances the flexibility and operational acceptability of the system.

The data transfer process from the airborne system to the DRU evolved into one which was proven to be operationally acceptable. The DRU is adequately compact and portable, and does not require specialist skills to operate or assess displayed results at flight line level.

The trials system DRU functions were all password protected, including those at "Ground Crew", the lowest level of access. It was therefore necessary to perform a structured sequence of several distinct functions in order to transfer results from the airborne system and display them. As a result of trial experience and comment by flight line users, the production system has been revised so that the lowest level of access, "Flight Line", will not require a password to transfer and display the HUMS results. A single operation, which is defaulted to when the DRU is switched on, transfers and displays results with only one keyboard operation required. A password will still be required to transfer configurations to the airborne system, this function being accessible only at "Maintenance" level.

5.4.2 *Use of GSC*

The trial GSC was available to line engineers at Sumburgh, with an instruction sheet detailing basic operations. There was a high degree of positive interest in the GSC, although a few engineers showed some reluctance to use the computer, either out of concern that it would be too difficult to use, or that it would be possible to lose data or worse by carrying out an action incorrectly. This latter attitude, quite understandable among non-computer people, can be overcome with education and confidence building.

SOAP data was manually entered onto the trial GSC, and was freely available to all. Reports to the Base Engineers took the form of reduced copies of the analysis result record from Spectro Laboratories, backed up by screen prints of trend graphs from the GSC in the event that a significant trend increase became evident.

Assessment by line staff of data displayed on the GSC was not tested to the same extent as operation of the DRU, although it was felt that the data was presented in a satisfactory manner. Authorised users of the production HUMS GSC will undergo formal training in the use of the system and in data assessment procedures.

5.4.3 *Data storage/backup*

Regular disk backups of trial data were made and supplied to SHL, where they were used for analysis and development tasks. Retrieval and restoration of data from SHL was possible in the event of major problems with the trial GSC, but no such retrieval of data was required. The backup process worked satisfactorily, however a considerable number of disks were required when the database was approaching its maximum capacity. Data storage for the production systems will take the form of tape backups.

5.4.4 *Maintenance implications*

In respect of the trial system, the airborne components were initially approved for aircraft installation by BIHL Technical Services Section. In-service modifications to the units were entered onto record sheets for each unit, held jointly by the three trial participants.

Installation of equipment onto the trials aircraft was certified by the normal BIHL Technical Log system, and was performed by the BIHL Project Manager and BIHL line staff as required.

During the operational phase of the trial assistance of line staff was required for occasional defect investigations and system calibration checks. Defects were, in the main, the cable faults which are described in Section 5.2.2. As a matter of routine, the additional burden of the trial on the line level resources was insignificant in relation to the normal daily workload. When line staff assistance was required for in depth investigation of trial system problems, manpower allocation to HUMS work had to take second priority to the work required to meet flying commitments.

Production HUM systems will, when installed, demand full committment from engineering in order to maintain serviceability. This will apply particularly when maintenance or airworthiness credit is obtained. Significant periods of system unserviceability could jeopardise continued credits. This operational aspect of HUMS is discussed further in (7.2.1).

5.5 Transmission vibration monitoring experience

5.5.1 *Flight conditions for transmission health monitoring*

In defining flight conditions under which transmission health monitoring data is produced, two potentially conflicting requirements must be considered:

(1) To maximise airworthiness benefits it is desirable that the HUMS monitors the health of the transmission system for a high percentage of the time a helicopter is airborne.

(2) To maximise the stability of the results produced by the HUMS restrictions must be placed on the conditions under which transmission vibration data is acquired and analysed.

The trial HUM system monitored the following aircraft flight regime parameters:

- Combined engine torque
- Airspeed
- Altitude
- Air temperature

All vibration analysis results produced by the HUM system were tagged with these parameters. During the commissioning phase of the trial SHL allowed the HUM system to acquire and analyse data under all flight regime conditions to:

(a) Investigate the effects of aircraft flight regime on HUM system data.

(b) Determine what restrictions should be put on regime conditions for data analysis to obtain a satisfactory balance between the two conflicting requirements defined above.

Figure 5.1 shows probability density functions for the flight regime parameters using data recorded over a two week period of normal aircraft operations. These plots give a picture of the range of the regime values recorded and the percentage of time an aircraft spends at a particular flight condition. The data shows that, as expected, the aircraft operated for a large percentage of the time within a narrow range of torque and airspeed values. The spread of the altitude values showed that the aircraft routinely operated at different altitudes in the range 0 to 3,500 ft.

An analysis of the affects of the regime parameters on health monitoring data indicated that variations in engine torque increased the variability in the data. SHL concluded that satisfactory data stability could be obtained by placing limits on data acquisition based on selected regime parameters. It was estimated that the parameter limits would result in a loss of only approximately 15% of the total possible aircraft monitoring time. The HUM system was modified to acquire and analyse transmission vibration data when the aircraft was in a cruise condition, defined as:

- Commencing 5 minutes after takeoff, subject to selected flight regime parameters being within specified limits.

Integrating the HUMS with an FDR in the production system has enabled the HUMS to have access to a larger number of flight regime parameters which are acquired by the FDR. This will provide further scope for refining the automated control of the HUMS data acquisition processes.

5.5.2 *Transmission vibration monitoring data*

This section reviews the transmission health monitoring data produced by the prototype HUM system after completion of the commissioning phase. The data is from gearbox A14-974 in aircraft G-BEIC and was acquired over a period of 728 flying hours.

The system commissioning phase was completed shortly after installation of gearbox A14-974 in G-BEIC. The HUMS was initially set in 'learning' mode to generate statistically based thresholds for the vibration analysis indicators using approximately the first 50 analysis results. The HUMS was subsequently allowed to generate data over a period of 678 hours to enable an assessment of both the short and long term stability of the health indicator values produced.

Examples of the transmission vibration monitoring data produced by the HUMS are presented in Figures 5.2 to 5.6. These show trend plots of 4 indicators over the 728 hour period for 5 gear shafts in the main gearbox. Downloads from the HUMS were taken on average once a day and the plots show an average of approximately 650 data points. The horizontal axes of the plots are gearbox hours (top set of numbers) and aircraft hours.

The 4 transmission health indicators selected (RMS, FM1A, FM4A, FM4B) represent 1 energy indicator and 3 pattern indicators. As the bounds of the pattern indicators are known it is possible to use these indicators to assess the quality of the data being produced by the prototype system. For example the FM1A and FM4B indicators are bounded to an approximate range of 0-1, the FM4A indicator has an ideal no-fault value of 3.0 and can rise to values as high as 25 under tooth damage or fatigue cracking conditions.

The following points can be made about the transmission vibration monitoring data produced by the prototype HUMS:

(1) Figures 5.2 - 5.6 show that the prototype HUM system is producing good quality transmission health monitoring data for both high and low speed gears in the main rotor gearbox. Good data was also produced for the intermediate and tail gearboxes. The data suggests that the desired airworthiness benefits can be obtained from on-board vibration based health monitoring of the transmission system. The results have given no indications of damage in gearbox A14-974.

(2) The vibration monitoring techniques have been readily applied to the S61 transmission system, with no aircraft type specific adaption of health indicator algorithms. The experience indicates that the techniques can be applied to different aircraft types with little difficulty.

(3) The health monitoring indicators showed good long term stability. Some minor changes in the data were observed over the 728 hour monitoring period, resulting in occasional crossings of the statistically learnt 'caution' threshold. This must be taken into account in the threshold setting policy to prevent a false alarm problem. Threshold setting procedures can be refined once experience has been gained monitoring multiple aircraft over a period of time.

(4) Occasional 'outliers' are present in the data, these are single results which clearly do not fit the distribution of the remaining data. These may be the result of a flight regime effect not taken into account in the prototype HUM system. Outliers can easily be removed by techniques such as 'binary integration' and therefore would not cause a false alarm problem. Improvements to the primary analysis function in the production HUMS has effectively eliminated the the occurrence of outliers.

(5) Figures 5.4 and 5.5 show indicator trend plots for the main bevel input and main bevel. The gap in the plots was caused by disbonding of an accelerometer which resulted in a cable failure. The failure was detected by the BITE, the system stopped producing data and did not generate any spurious results.

(6) Figures 5.2-5.6 show that, although all trend plots show a good grouping of results, moving from the high speed input gears to the low speed output there is an increasingly tight grouping of indicator values. This is to be expected, and is due to the increased dynamic stability of a high torque low speed gear compared to a high speed low torque gear. For the same reason, some of the indicators for the gears in the lower torque tail drive showed a small reduction in the tightness of the grouping of values.

(7) The data presented in Figures 5.2-5.6 is considered to be of good quality, capable of interpretation in a straightforward manner. The trial indicated one area where the transmission vibration data was more difficult to interpret. Indicator trend plots for the starboard freewheel showed that, whilst FM4A values were stable, there was variability of those indicators which included gear meshing frequency vibration data in their computation, making the interpretation of these indicators difficult. Some variability was also seen

in the results for engine 2 input gear, but to a lesser extent. An investigation showed that the variability was caused by an unstable gear meshing tone. The reasons for the behaviour of the gear vibration are not fully understood, but may be associated with the dynamics of the starboard freewheel shaft and the behaviour of the freewheel unit. From the point of view of vibration health monitoring, the problem can be addressed by modification of the suite of health monitoring indicators to eliminate any dependencies on the gear meshing tone, possibly coupled with a tightening up of the conditions for vibration data acquisition.

(8) The results obtained from the prototype system are very encouraging, particularly when improvements which are being incorporated in the production HUM system are taken into account. Data from the production system shows further improvements in quality and stability. The airworthiness benefits which can be obtained will by maximised by an on-going process of learning from the experience gained from long term monitoring of a fleet of aircraft.

In order to assess how the trial vibration data relates to the condition of gearbox A14-974 a detailed strip examination and report is required. The gearbox strip report will be published as an annex to the main report.

5.6 Analysis of engine monitoring and usage data

Sources of data

Three main sources of data were available. These are:

- Ground station output
- Engine monitoring tape recorder output
- BIHL's existing manually logged data

Ground station output

The ground station provided access to results data in a 'high level' format via a number of different screens dedicated to specific engine monitoring functions. The types of data presentation available have already been described elsewhere in this report.

Engine monitoring tape recorder

The main components of the HUMS system have already been described elsewhere in this report. In addition to these items a Penny and Giles data recorder was fitted for the later stages of the trial. This recorder was connected to a serial datalink on the Data Management Card within the MPU.

When engines were running, engine and airframe parameter data was transmitted to the recorder together with time and date information. On engine shutdown, results data was sent to the recorder in place of the regular stream of engine and airframe parameters. The data was stored on standard magnetic tape cartridges which were replayed on a compatible office based unit at HSDE's Welwyn Garden City premises.

Existing manually logged data

As part of their existing procedures, BIHL log a number of parameters manually for each aircraft. These include airframe hours, flight times, number of take-offs, and daily PAC checks on each engine. This data has been correlated against the HUMS recorded results data. The correlation has shown a very close agreement in the manually and HUMS logged usage data over a long period of time. This confirmed that the HUMS was correctly logging usage data and also that data logged manually is accurate.

Engine monitoring systems results

The data recorded represented an elapsed time of some 750 airframe hours. Analysis of the results is continuing and some 34 tapes have been received from BIHL.

An analysis of the results available from the GSC and the manually recorded data produced by BIHL showed that HUMS was logging engine monitoring data correctly. The tape data analysed agreed well with the other data sources.

HUMS logged PAC data showed consistency with the manually logged data within the expected tolerances. Little topping and limit exceedance data was available, this is as expected as topping checks are rarely performed and limit exceedances are in practice rare events.

5.7 Oil and debris analysis

BIHL are conducting a SOAP (Spectrographic Oil Analysis Programme) on the entire S61 fleet. The SOAP data for all aircraft was manually entered into the HUMS GSC and stored in a separate SOAP database. BIHL consider that, with HUMS, SOAP and tribology data available on a single computer, a system offering comprehensive condition monitoring data was available to line level engineering personnel.

The oil analysis routine adopted by BIHL has been for samples to be taken from the S61 fleet main gearboxes, and analysed by Spectro Laboratories, at 50 hour intervals. The trial aircraft had additional samples taken at the same time, which were monitored for PQ Index and debris nature by The Swansea Tribology Centre.

The procedure BIHL has adopted of using Spectro Laboratories for routine monitoring, with additional samples assessed by The Swansea Tribology Centre as required, is considered to have been satisfactory to date. In the event that a significant trend or level is observed in the Spectro data, additional samples are taken and sent to Swansea for RPD debris separation, PQ Index measurement and debris analysis. In this way, the two different techniques are felt to complement, rather than supplant, one another.

The cost of SOAP to BIHL is estimated at £35 per sample (or approximately 70 pence per flight hour). This represents the cost of the analysis, the time for BIHL staff to take the sample, and the expendables of padded envelope and sample bottle. Samples are sent to Spectro Laboratories by normal mail, with results usually being available within two days of the sample being taken. Results are notified to BIHL by telex for each individual sample, with a monthly report covering all aircraft being presented in the form of a computer printout.

Each spectro sample is monitored for the presence of 17 metallic elements. Distribution plots for each element are produced on a 3 monthly basis by Spectro Laboratories, and show the values of all samples received. Each aircraft record can be compared to the others in the fleet, providing an impression of how much an individual gearbox is deviating from what can be considered the normal. Figure 5.7 is the distribution plot for iron.

Most of the Spectro analysis functions are automated, ensuring a high degree of consistency from one result to the next. Experience has shown that deviations from the normal gradually increasing trend which may indicate a deterioration in gearbox condition are readily apparent, Figure 5.8 and Figure 5.9.

The analyses performed by the Swansea Tribology Centre (2.4.2) were costed at £40 per sample. Results were available within 3 or 4 days from sampling, and were communicated to BIHL by post in the form of a brief report detailing debris nature and sizes. Calibration of the PQ Index measuring instruments was performed prior to each sample test, using a test specimen of known value. In this way confidence in the consistency of result values was high.

5.7.1 *On-line oil debris monitoring experience*

Initial problems encountered with the Tedeco zapper chip detector have been discussed in Section 5.3. After these had been overcome installation testing was successfully completed. The modified Tedeco zapper fuzz burner chip detector then flew for approximately 350 hours monitoring gearbox A14-970 in G-BEIC without recording any zapper discharges.

During the 350 flying hours, the HUMS continuously recorded 'zero' zapper counts. In this period no debris or evidence of discharge was apparent on the chip detector, in the screen filter surrounding it, or in the main filter during scheduled inspections. The absence of debris or evidence of discharge on the zapper/chip detector unit reinforces the conclusion that the zapper was functioning correctly in that discharges were not being recorded.

5.7.2 *Oil analysis experience*

Main Gearbox serial no A14-215, G-BEOO

A significant decision based entirely on oil and debris analysis resulted in premature rejection from service of a main gearbox from a BIHL S61 in July of 1990. The first indication of a potential problem with the main gearbox of G-BEOO (not one of the HUMS trial aircraft) was at 11836 airframe hours, when an oil sample was sent by mistake to the Swansea Tribology Centre, rather than the correct destination of Spectro Laboratories.

The PQ Index was measured at 45, compared to an average value of 15 recorded to that date for the trials gearboxes, Figure 5.10. Particle size was also significantly larger than average, at 220μm. Previous Spectro samples did not give any cause for concern, with only iron showing a slightly high but not exceptional level.

At 11920 airframe hours, when the Spectro iron level had reached 51.5ppm, the oil sampling frequency was increased to daily sampling. Over the next 100 flying hours an increasing trend for iron, chrome and nickel content became evident in the Spectro results. The peak increase occurred between 12008 and 12016 hours, iron increased from 48 to 74ppm, an hourly rate of increase of 3.25ppm. Iron remained above 70ppm for 20 hours, dropping rapidly at 12046 hours. The levels of chrome and nickel followed the trend of iron very closely, Figure 5.8.

Consultation with Spectro suggested that the reduction in levels in the Spectro samples could be due to a change in the nature of wear or other distress occurring in the gearbox. At 12016 hours a sample was provided to Swansea Tribology Centre. The PQ Index had reached 65, and particle size had increased to 580μm. There was also evidence of overheating, with particle blueing evident and, for the first time in a BIHL gearbox, friction polymers (produced by extreme gear pressure and high temperatures) were present in a significant quantity.

These results were available to BIHL at 12060 hours, on 23rd July. On the basis of the trends and apparent correlation displayed by the two analysis techniques, the decision was taken to withdraw the gearbox from further commercial flight, with 375 hours of overhaul life remaining. The gearbox was returned to Sikorsky for overhaul. BIHL were advised verbally of component wear which rendered the (unspecified) items unsuitable for reuse in the overhauled gearbox, however nothing indicative of impending failure was evident.

Main gearbox serial no A14-1064, G-AYOM

In February/March of 1991 rising trends were seen in the SOAP data for this gearbox (the gearbox was again not part of the HUM trial). Levels of magnesium, aluminium and lead were above normal and increasing, lead at a rapid rate but not at the Sikorsky S61 maintenance manual alert level of 1ppm/flying hour, sustained for 6 hours.

The plots for magnesium, aluminum and lead are given as Figure 5.9. As the gearbox was almost due for midpoint service, the sampling interval was reduced to 25 hours and the box continued in service.

Three samples were analysed by the Swansea Tribology Centre prior to removal of the gearbox. The PQ Index of all three was in the normal range, as shown in Figure 5.10. Particle sizes were higher than average but were not exceptional. Inspection of the gearbox at Aberdeen showed significant but not unusual wear of the right hand input plain white metal bearing. The bearing was acceptable for reuse, and was retained in the gearbox after inspection. The gearbox was subsequently returned to service in G-BCEA, with the normal 50 hour Spectro sampling being carried out.

It is of note that gearbox A14-215 was observed to have first deviated from normal values in respect of the PQ Index, Spectro samples did not indicate a significant trend for some time afterwards. Gearbox A14-1064, however, did not register an exceptional PQ value, while the levels of lead and magnesium measured by Spectro were well out of what BIHL has come to regard as the normal range for the S61N. Note that on Figure 5.9 the levels of each metal dropped after the midpoint service, when the gearbox oil was drained. Experience has shown that when damage or wear is present the trends will begin to rise again. After midpoint service, gearbox A14-1064 was installed in G-BCEA, and removed from service shortly after installation, as a result of a problem related to the accessory drive train. There was no evidence to connect the oil analysis results to the eventual reason for removal.

Main gearbox A14-974, G-ATFM and G-BEIC

This is the gearbox for which most of the flight trial vibration analysis data was obtained. The gearbox was installed in G-BEIC when the FDR/HUMS installation was embodied in G-ATFM during March/April of 1991. The gearbox was thus monitored by an airborne HUMS and two off-line oil analysis techniques for 1217 flying hours.

Figure 5.11 traces the gearbox SOAP history from post midpoint installation in G-ATFM. The figures in the column 'Cust Ref' are the airframe hours at which the sample was taken. The figures in the columns headed by metallic element symbols are the content in parts per million (PPM) of the sample. A gradual increase is evident in the levels of Fe, Cu, Pb, Ti Pb and Zn.

On removal for installation in G-BEIC, Figure 5.12, it is evident that the values have dropped after the oil change carried out during gearbox removal. A trend of gradual increase is again evident from the samples during service life up to the point of removal.

There are no levels recorded at any stage during the post-mid-point service life which would give BIHL cause for concern.

Tribology analysis of the gearbox was also performed during this period, with samples taken at the same time at those for Spectro. Figure 5.10 is a distribution plot for the PQ values of all BIHL S61 gearbox oil samples tested by the Swansea Tribology Centre in the course of the trial. There is a clear concentration of results in the range 10 to 17. BIHL and Swansea agree that these values represent the normal for the S61 in BIHL operation. Gearbox 215, as described above, is the only instance where values significantly higher were recorded.

This experience reinforces BIHL's view that the PQ Index is a valuable indicator of debris production, of ferrous debris in particular. For BIHL's UK operations, the PQ Index will be employed in support of a more general oil analysis technique, equally sensitive to ferrous and non-ferrous metals, of which Spectro analysis is favoured.

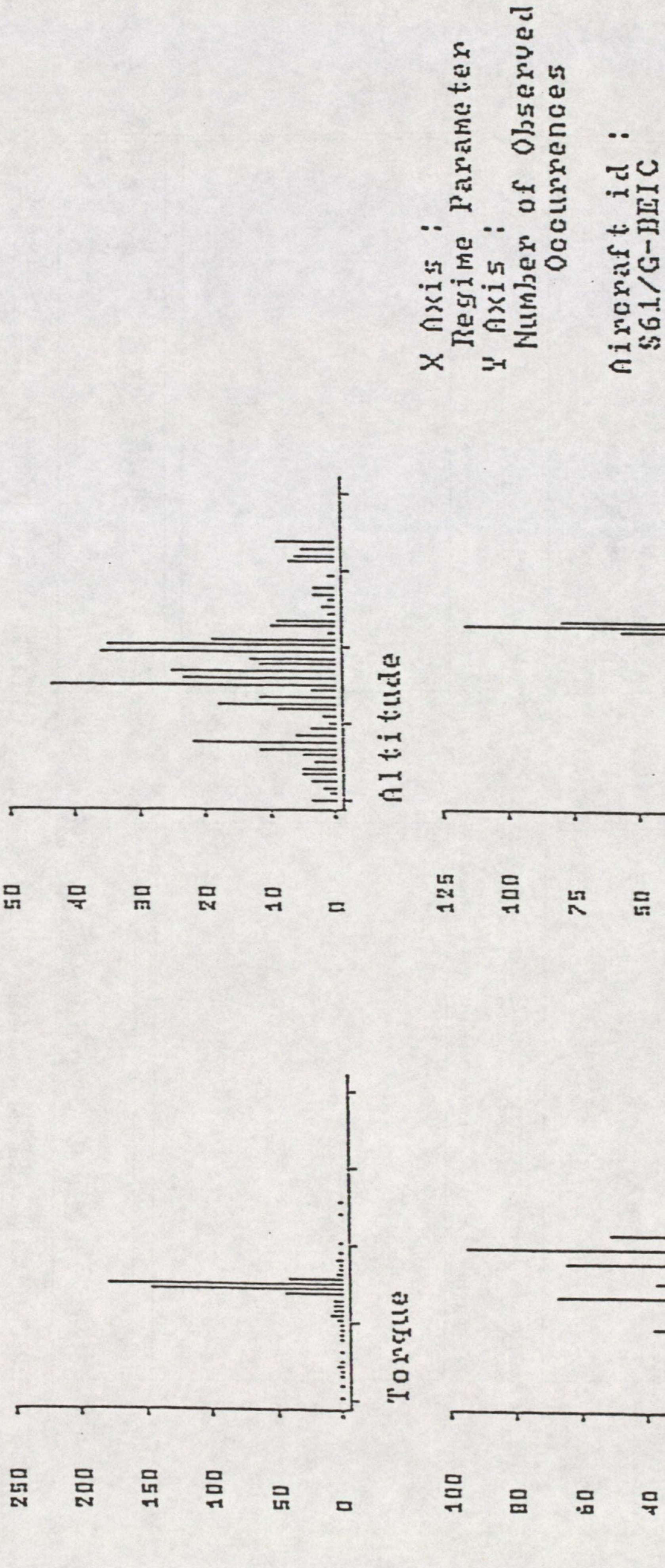


FIGURE 5.1 : Observed regime parameter variations

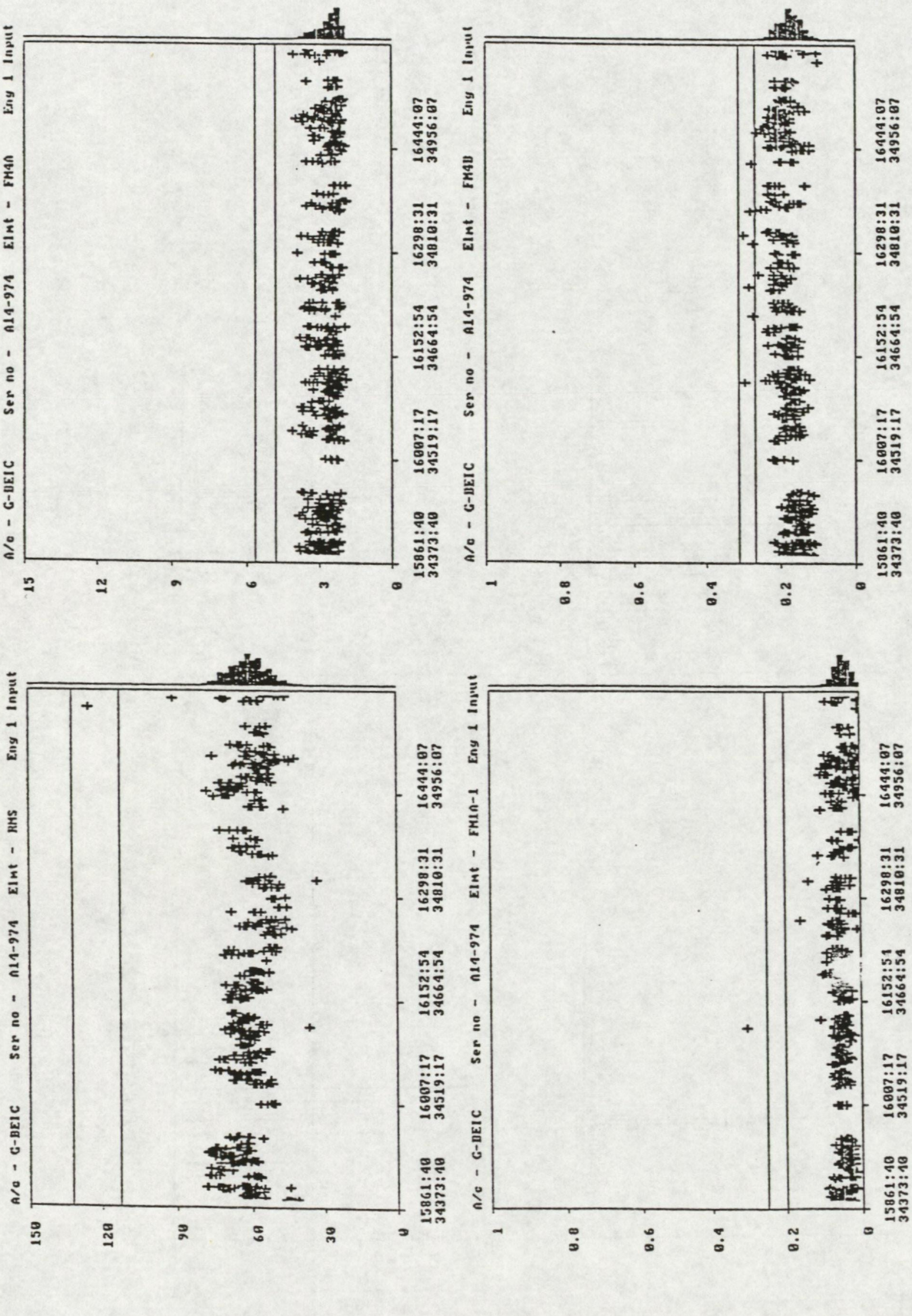


FIGURE 5.2 : Indicator trend plots for Eng 1 input

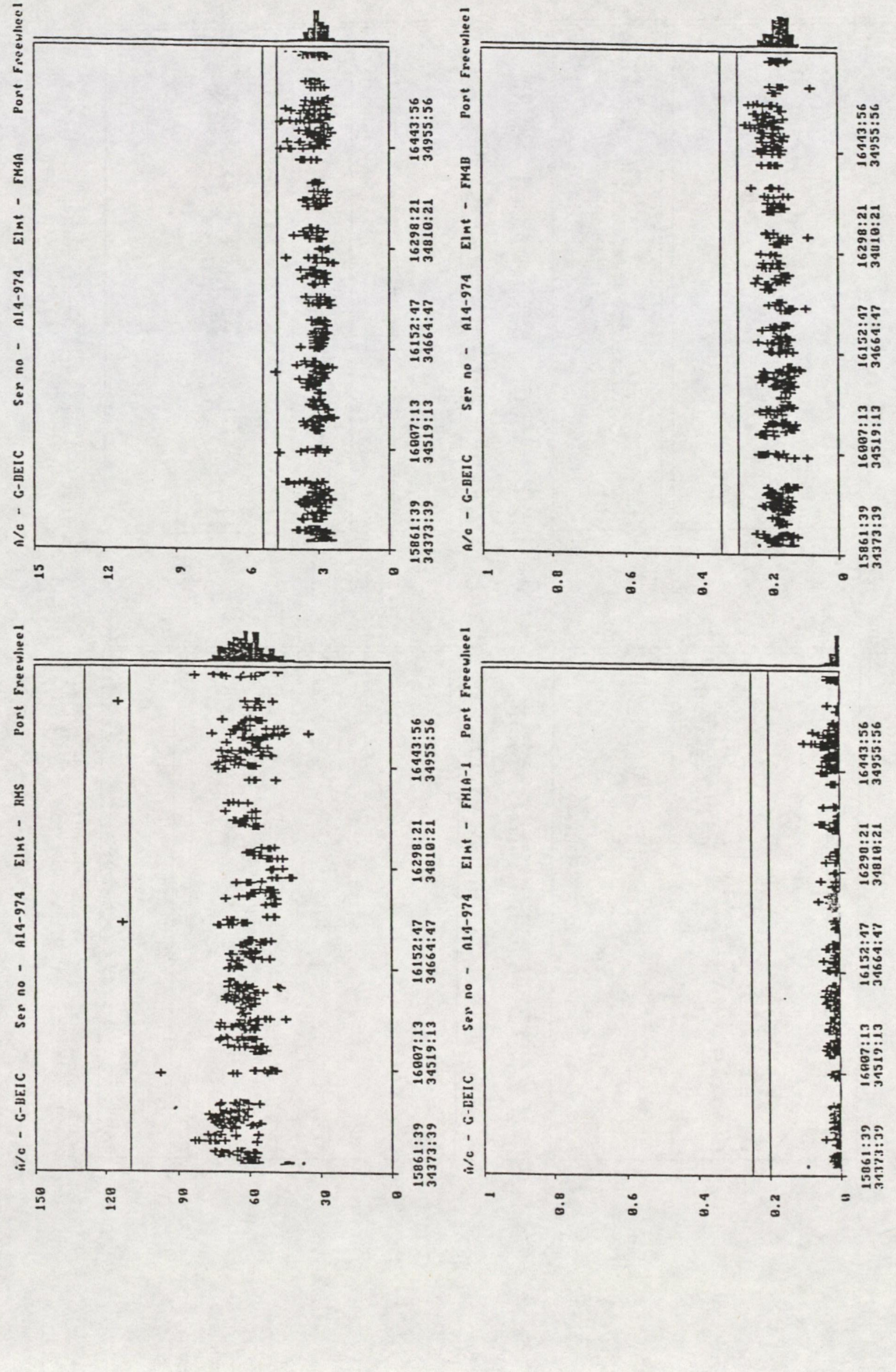


FIGURE 5.3 : Indicator trend plots for Port freewheel

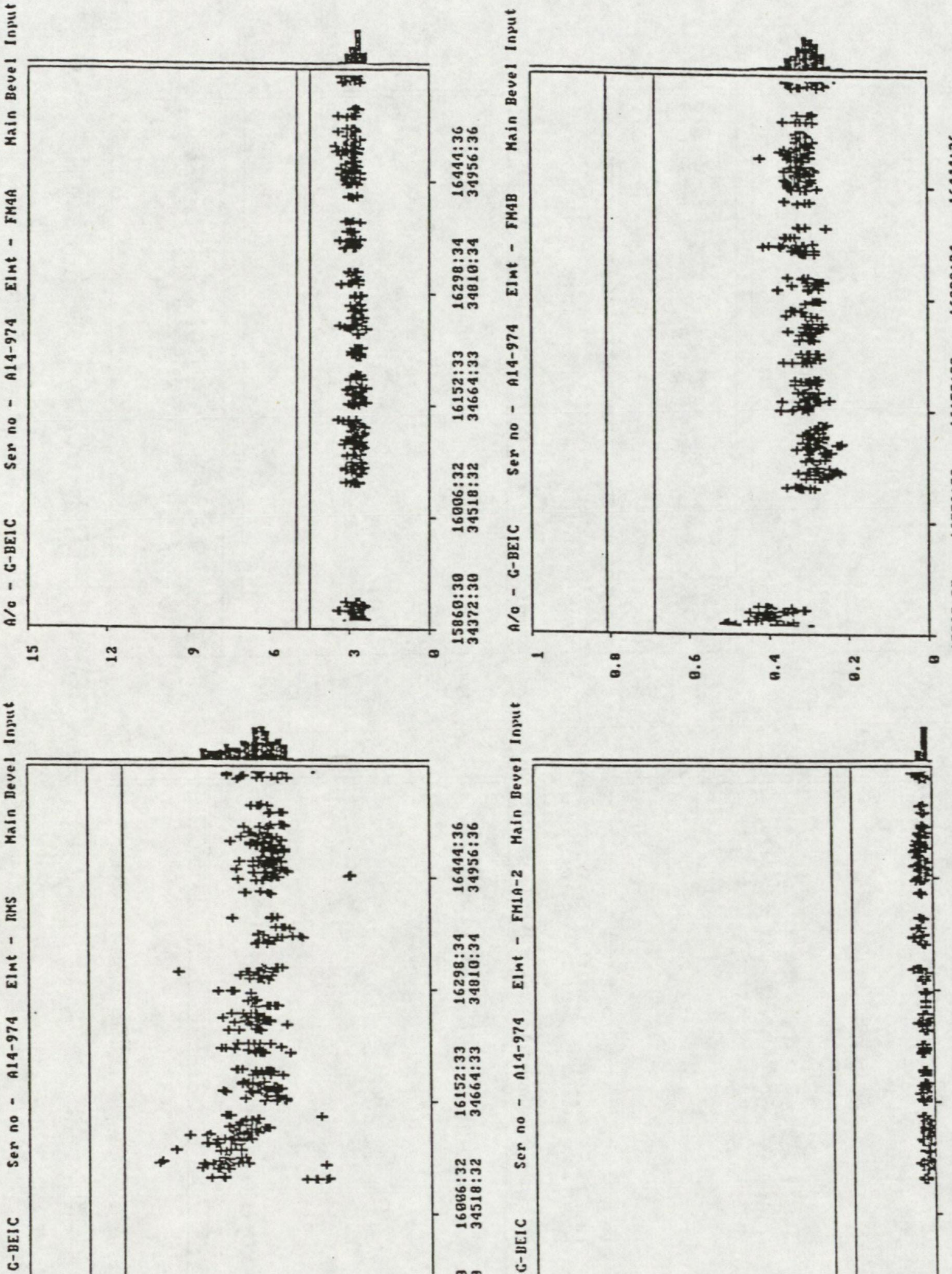


FIGURE 5.4 : Indicator trend plots for Main Bevel input

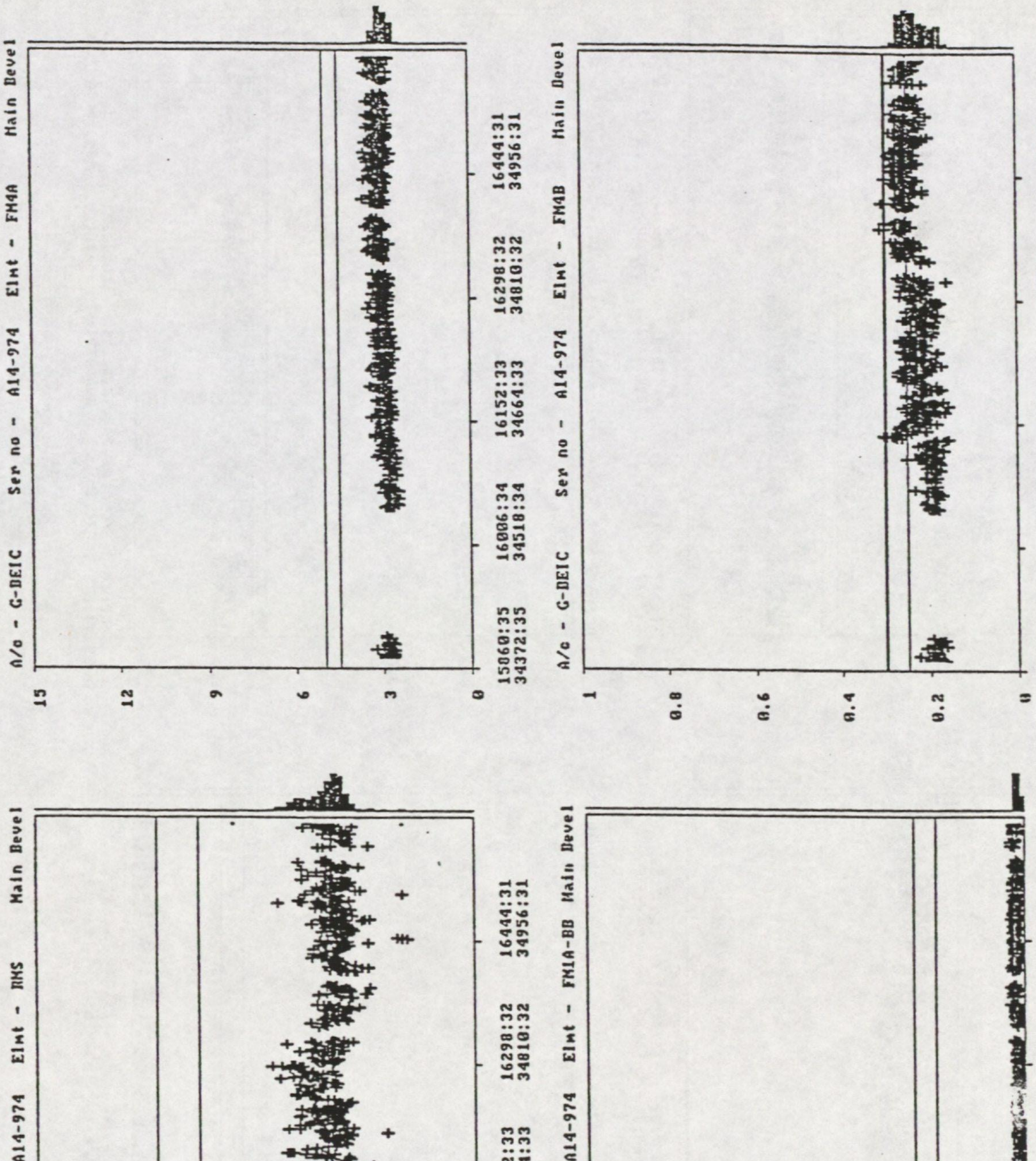


FIGURE 5.5 : Indicator trend plots for Main Bevel

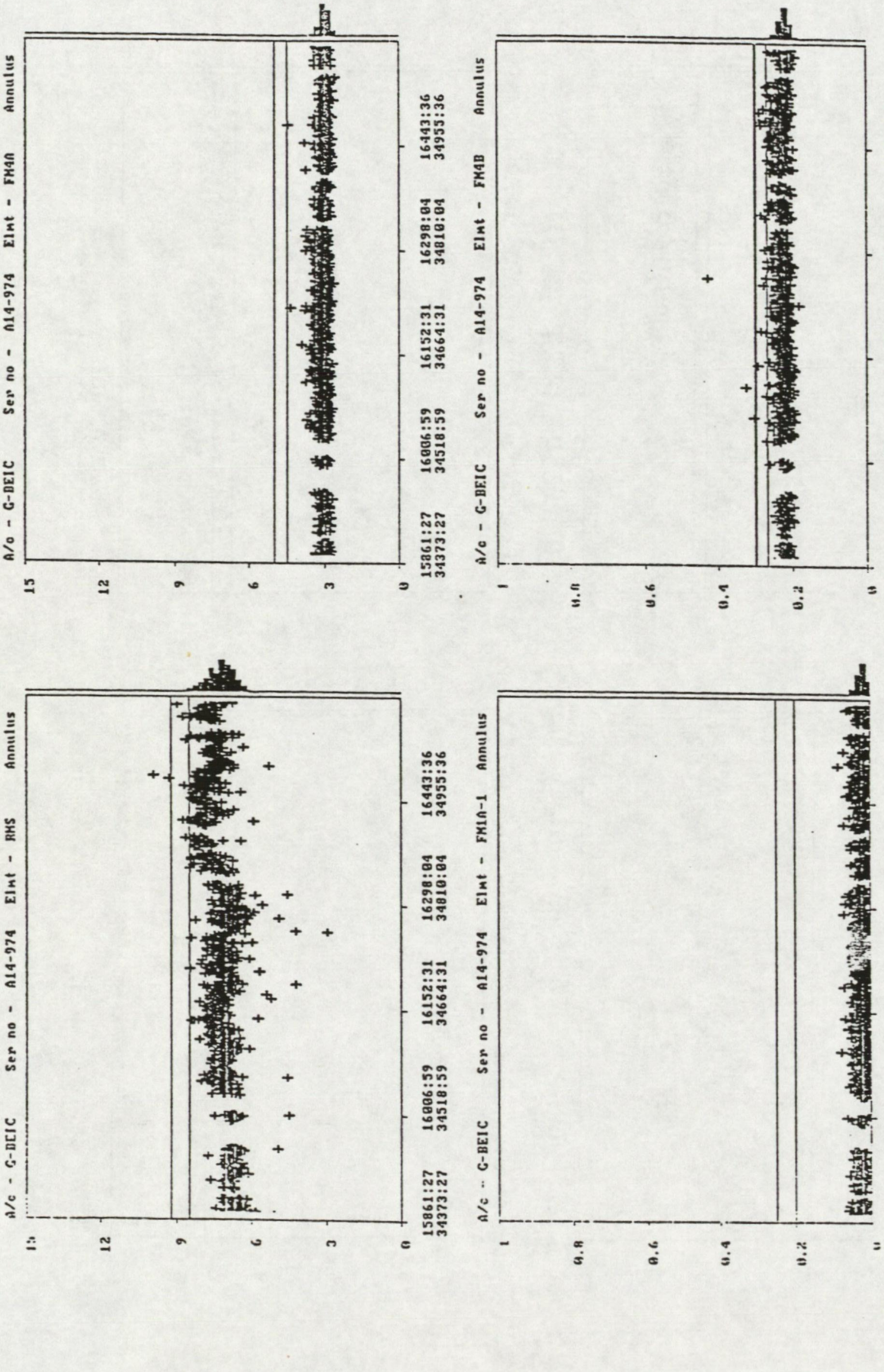
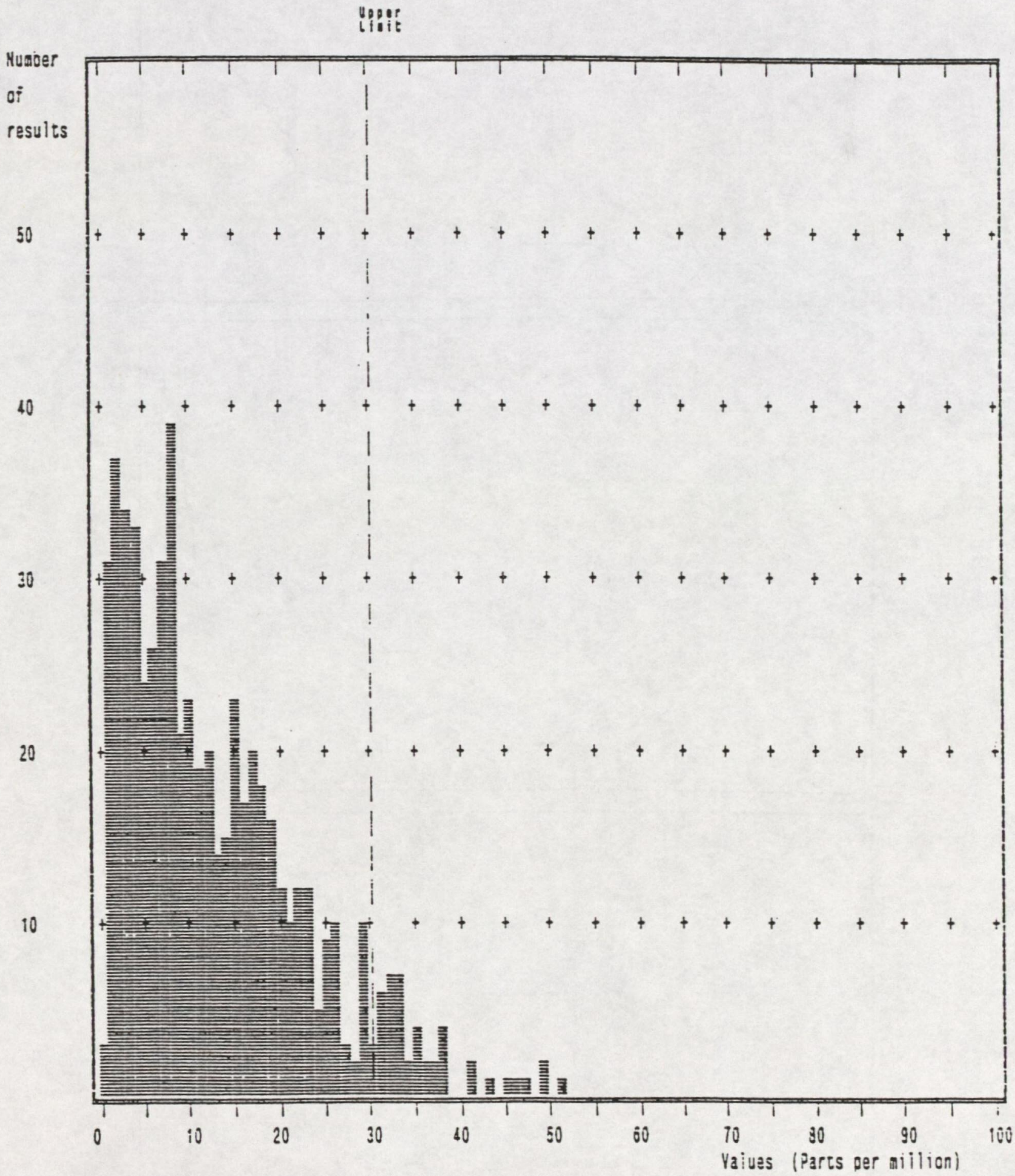


FIGURE 5.6 : Indicator trend plots for Epicyclic Annulus

Distribution Of Results For IRON

British International Helicopters - all main gearboxes. - Rec Nos MG8BJ to MGBWM
Lowest value .8 Highest value 51.3
Upper limit 30
Number of results 595 As at 4th December 1991.



British International Helicopters - all main gearboxes. Page
Print Date 06/12/91 IRON

FIGURE 5.7 : SOAP data - distribution of results for iron for all main gearboxes

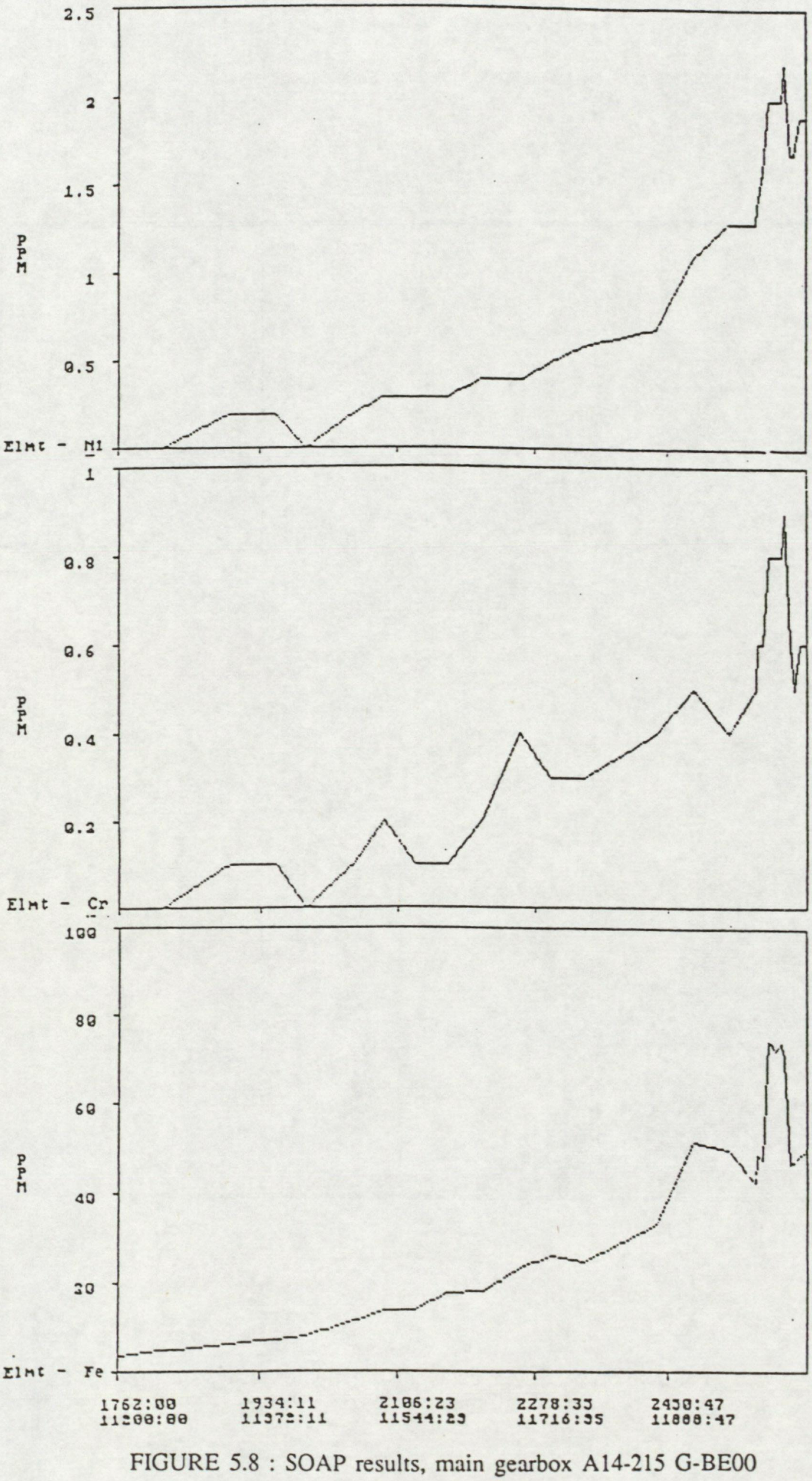


FIGURE 5.8 : SOAP results, main gearbox A14-215 G-BE00

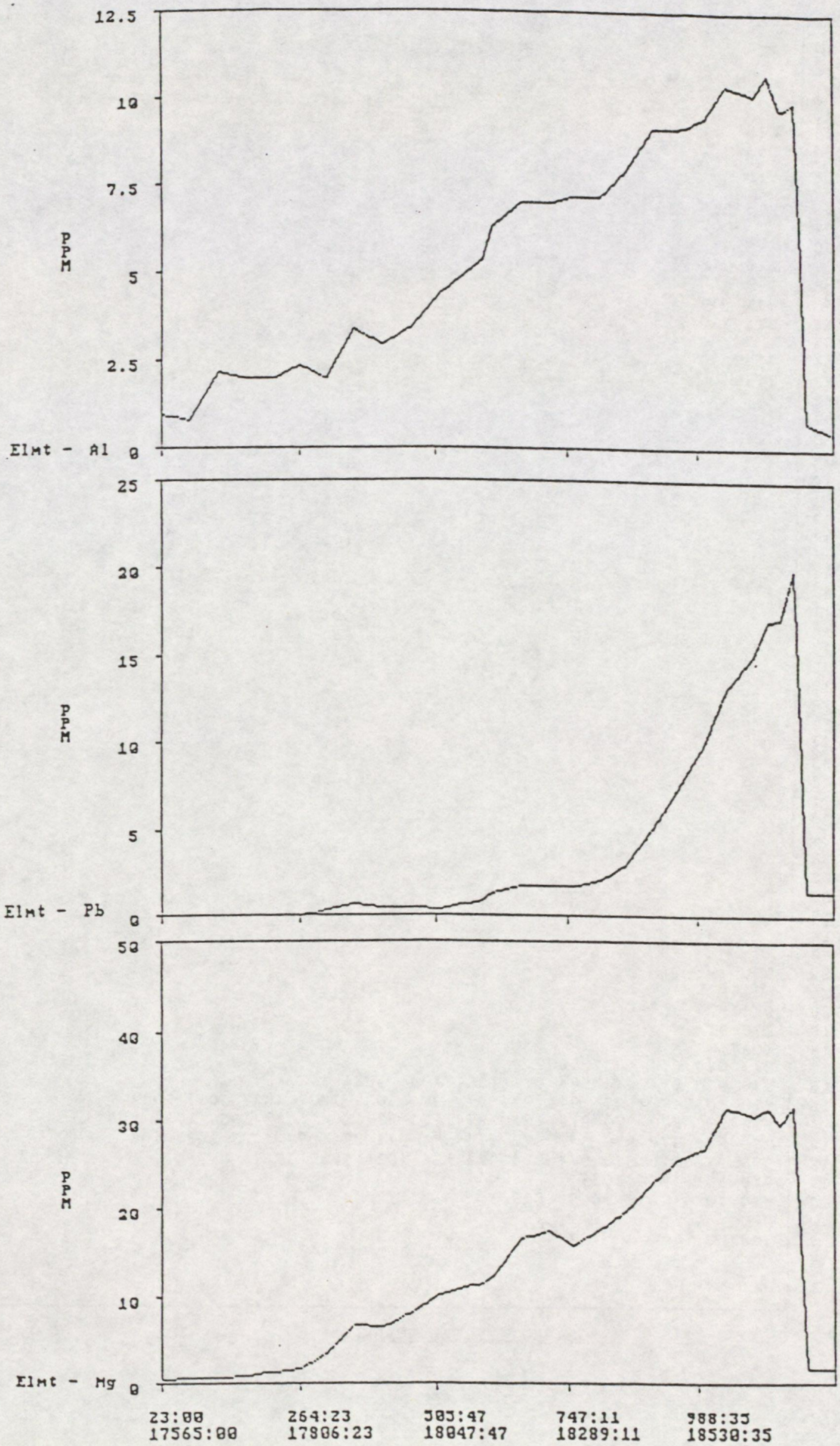


FIGURE 5.9 : SOAP results, main gearbox A14-1064 G-AYOM

PQ INDEX	GEARBOX SERIAL NUMBERS
70	
69	
68	
67	
66	215
65	215
64	
63	
62	215 215 215
61	
60	
59	215 215
58	
57	215
56	215 215 215 215
55	
54	215 215 215
53	215
52	
51	
50	
49	
48	
47	
46	
45	215
44	
43	
42	215
41	
40	
39	
38	
37	1019
36	
35	
34	
33	
32	215
31	
30	
29	
28	
27	
26	
25	
24	
23	
22	970
21	
20	974
19	970 974
18	1037
17	970 974 974 1037 1037
16	970 970 974 974 974 974 1037 1064 1064
15	970 1019 974 974 974 974 974 974 1037 1037 1037 1037 1064
14	970 970 970 970 970 1019 974 974 974 974 1037 1037 1037 1037
13	970 970 970 970 970 970 974 974 974 974 974 1037 1037 1037
12	970 970 970 970 974 974 974 974 1019 1037 1037
11	970 1019 974 1037
10	970 1019 1019 1019 1019
9	970
8	1037
7	
6	
5	

Serial Number	Number of samples
215	19
970	23
974	28
1019	9
1037	19
1064	3
	101

FIGURE 5.10 : PQ index values

SPECTRO - Oil Analysis Results. Print out of all units

A/C REG G-ATFM SER No A14-805 OPERATOR:- British International Helicopters EQUIPMENT TYPE M.G.B. OIL TYPE EXXON 274

Test Date	Sample Date	Lab Ref	Cust Ref	Fe	Cr	Mo	Al	Cu	Pb	SN	Ag	Ni	V	Ti	Si	Na	B	Mg	Ca	W	P	Zn	Fuel	Solids	Water	Visc @40	Visc @100	Photo	TAN	TBN	
09/03/90	05/03/90	C593	22580	16.3	.3	0	1.8	1.5	.5	0	.1	.3	.2	3.9	1	0	0	3.3	0	0	0	1.3	-	-	-	-	-	-	-	-	
15/03/90	12/03/90	C928	22615	16.8	.3	0	1.6	1.6	.4	0	0	.3	.3	4.2!	1	0	0	3.6	0	0	0	1.4	-	-	-	-	-	-	-	-	ALERT
28/03/90	22/03/90	C1815	22661	17.5	.2	0	1.5	1.9	.3	0	.1	.3	.3	4.3!	0	0	0	3.5	0	0	0	1.4	-	-	-	-	-	-	-	-	ALERT
18/04/90	11/04/90	D1057	22708	18.4	.3	0	2	1.9	.4	0	.1	.3	.3	4.7!	1	0	0	3.8	0	0	0	1.5	-	-	-	-	-	-	-	-	ALERT 4P
25/04/90	20/04/90	D1508	22754	19	.3	0	1.7	2	.4	0	.1	.3	.2	5!	1	0	0	4	0	0	0	1.5	-	-	-	-	-	-	-	-	ALERT
08/05/90	01/05/90	E419	22802	22.3	.5%	0	2.8%	2.2	.6	0	.1	.3	.4!	5.8!	1	0	0	4.7	0	0	0	1.8	-	-	-	-	-	-	-	-	ALERT
19/05/90	07/05/90	E1154	22835	24.4	.4	0	2.7	2.2	1	0	0	.3	.4!	6!	0	0	0	4.9	0	0	0	1.9	-	-	-	-	-	-	-	-	ALERT
18/05/90	07/05/90	E1155	22835	24.7	.4	0	2.7	2.2	1	0	0	.3	.4!	6.2!	0	0	0	4.9	0	0	0	1.9	-	-	-	-	-	-	-	-	ALERT
18/05/90	15/05/90	E1156	22866	24.8	.4	0	2.7	2.2	.8	0	0	.3	.4!	6.2!	0	0	0	4.8	0	0	0	1.8	-	-	-	-	-	-	-	-	ALERT
24/05/90	15/05/90	E1535	22866	20.4	.3	0	2.4	2	.6	0	.1	.5	.3	5.3!	0	0	0	4	0	0	0	1.5	-	-	-	-	-	-	-	-	ALERT
05/06/90	28/05/90	F302	22917	19.8	.3	0	2.4	2.2	.5	0	.1	.5	.3	5.2!	0	0	0	3.7	0	0	0	1.4	-	-	-	-	-	-	-	-	ALERT
08/06/90	05/06/90	F546	22952	22.9	.4	0	2.3	2.5	.6	0	.1	.5	.4!	6.3!	0	0	0	4.2	0	0	0	1.6	-	-	-	-	-	-	-	-	ALERT
27/06/90	14/06/90	F1701	23000	22.9	.3	0	2	2.2	.9	0	0	.5	.3	5.8!	0	0	0	3.9	0	0	0	1.2	-	-	-	-	-	-	-	-	ALERT
Change on 30/06/90							Removed :- 1037							Reason :- Time expired																	
06/07/90	03/07/90	G398	23044	3.2	0	0	.8	.3	0	0	0	.1	0	.2	0	0	0	1	0	0	0	.6		-	-	-	-	-	-	-	
24/07/90	17/07/90	G1606	23087	4.7	0	0	1	.7	0	0	.1	.1	.2%	.4	0	0	0	1.4	0	0	0	.9	-	-	-	-	-	-	-	-	R.O.C
01/08/90	30/07/90	H005	23132	5	0	0	.3	.5	0	0	0	.1	0	.4	0	0	0	1.4	0	0	0	1	-	-	-	-	-	-	-	-	
11/08/90	09/08/90	H649	23177	5.8	0	0	.5	1	0	0	.1	0	.2	.5	0	0	0	1.5	0	0	0	1.1	-	-	-	-	-	-	-	-	
30/08/90	28/08/90	H1846	23211	8.4	0	0	.5	1.1	.5	0	0	.1	0	.9	0	0	0	2.3	0	0	0	1.4	-								
24/09/90	19/09/90	J1402	23300	8	0	0	.4	1	.4	0	0	.1	0	.8	1	0	0	2.2	0	0	0	0	-								
29/09/90	27/09/90	J1803	23347	10.4	0	0	1	1.2	1	0	.1	.2	.1	1	0	0	0	2.9	0	0	0	1.5	-								
10/10/90	08/10/90	K594	23388	10.4	.1	0	.6	1.3	1	0	0	.2	0	1	0	0	0	2.9	0	0	0	1.3	-	-	-	-	-	-	-	-	
25/10/90	23/10/90	K1533	23439	12.6	0	0	0	1.4	.5	0	0	0	0	1.2	1	0	0	3.6	0	0	0	1.4	-	-	-	-	-	-	-	-	
07/11/90	05/11/90	L397	23480	13.5	.1	0	1.2%	1.5	1.2%	0	.1	.2	.1	1.4	0	0	0	4	0	0	0	1.5	-	-	-	-	-	-	-	-	R.O.C
19/11/90	15/11/90	L1082	23528	15.1	.1	0	1	1.7	1.2	0	0	.2	.1	1.5	0	0	0	4.4	0	0	0	1.4		-	-	-	-	-	-	-	
Change on 01/12/90							Removed :- A14-974							Reason :- HUMS trial gearbox, swapped to G-BEIC.																	
12/04/91	10/04/91	D680	23576	1.2	0	0	.2	.3	0	0	0	0	0	0	1	0	0	.3	0	0	0	.2	-	-	-	-	-	-	-	-	
25/04/91	23/01/91	D488	23621	2	0	0	0	.3	0	0	0	0	0	0	0	0	0	.5	0	0	0	1.3	-	-	-	-	-	-	-	-	
16/05/91	14/05/91	E812	23667	2.5	0	0	.5	.4	0	0	0	.2	0	0	0	0	0	.5	0	0	0	.7	-	-	-	-	-	-	-	-	
01/06/91	30/05/91	F017	23715	1.6	0	0	0	.3	0	0	0	0	0	0	0	0	0	.4	0	0	0	.3	-	-	-	-	-	-	-	-	
27/06/91	18/06/91	F1475	23774	1	0	0	0	.3	0	0	0	0	0	0	0	0	0	.3	0	0	0	.3	-	-	-	-	-	-	-	-	
19/07/91	03/07/91	G1184	23824	1.6	0	0	.4	.3	0	0	0	0	0	0	0	0	0	.4	0	0	0	.6	-	-	-	-	-	-	-	-	
10/08/91	22/07/91	H485	23872	2.3	0	0	0	.4	0	0	0	0	0	0	0	0	0	.5	0	0	0	.7	-	-	-	-	-	-	-	-	
10/08/91	07/08/91	H486	23920	1	0	0	0	.2	0	0	0	0	0	0	1	0	0	.3	0	0	0	.3	-	-	-	-	-	-	-	-	
30/08/91	23/08/91	H1566	23961	1.7	0	0	0	.4	0	0	0	0	0	0	1	0	0	.3	0	0	0	.3	-	-	-	-	-	-	-	-	
21/09/91	18/09/91	J1153	24020	2.6	0	0	0	.5	0	0	0	.1	0	0	0	0	0	.5	0	0	0	.6	-	-	-	-	-	-	-	-	
07/10/91	29/09/91	K463	24055	1.3	0	0	0	.4	0	0	0	0	0	0	0	0	0	.4	0	0	0	.2	-	-	-	-	-	-	-	-	
18/10/91	16/10/91	K1023	24099	2	0	0	0	.6	0	0	0	0	0	0	0	0	0	.4	0	0	0	.5	-	-	-	-	-	-	-	-	
30/10/91	28/10/91	K1698	24126	1.8	0	0	.4	.6	0	0	.2%	.3%	.1	.1	0	0	0	.5	0	0	0	.6	-	-	-	-	-	-	-	-	R.O.C
13/11/91	07/11/91	L600	24171	1.6	0	0	.3	.5	0	0	.1	0	0	0	1	0	0	.6	0	0	0	.8	-	-	-	-	-	-	-	-	
20/11/91	18/11/91	L933	24216	1.6	0	0	.2	.6	0	0	0	0	0	0	0	0	0	.9	0	0	0	.7	-	-	-	-	-	-	-	-	
28/11/91	26/11/91	L1359	24256	1.5	0	0	.2	.5	0	0	0	0	0	0	0	0	0	.8	0	0	0	.8	-	-	-	-	-	-	-	-	

Main Gearbox A14-974

RUN DATE 06-12-1991 File 2

SPECTRO OIL ANALYSIS COMPANY, Fairoaks Airport, Chobham. Woking, Surrey. GU24 8HU
Tel No 0276 857511 Telex 858133 SPCTRO G Fax 0276 856814

FIGURE 5.11 : SOAP data - gearbox 974 in aircraft G-ATFM

SPECTRO - Oil Analysis Results. Print out of all units

A/C REG G-BEIC SER No A14-974 OPERATOR:- British International Helicopters EQUIPMENT TYPE M.G.B. OIL TYPE EXXON 274

Test Date	Sample Date	Lab Ref	Cust Ref	Fe	Cr	Mo	Al	Cu	Pb	SN	Ag	Ni	V	Ti	Si	Na	B	Mg	Ca	W	P	Zn	Fuel	Solids	Water	Visc @40	Visc @100	Photo	TAN	TBN	
26/07/90		G1738	33547	9	.1	0	1.8	1.3	.2	0	.1	.2	.1	0	0	0	0	.7	0	0	0	.9	-	-	-	-	-	-	-	-	
08/08/90	03/08/90	H404	33587	2.5	.2	0	2.5	1.3	0	0	.1	0	.2	0	0	0	0	.5	0	0	0	1.8	-	-	-	-	-	-	-	-	
23/08/90	20/08/90	H1465	33633	9.6	.1	0	1%	1.4	0	0	.1	.1	.2	0	0	0	0	.8	0	0	0	.8	-	-	-	-	-	-	-	-	R.O.C
07/09/90	03/09/90	J415	33675	15.3	.2	0	1.1	1.8	.4	0	0	.3	0%	0	0	0	0	1.3	0	0	0	1.1	-	-	-	-	-	-	-	-	R.O.C
24/09/90	17/09/90	J1401	33720	12.7	.1	0	.6	1.5	0	0	0	.1	0	0	2	0	0	.8	0	0	0	.7	-	-	-	-	-	-	-	-	
28/09/90	26/09/90	J1723	33762	15.3	.2	0	.6	1.9	.3	0	.1	.3	0	0	0	0	0	1.2	0	0	0	.9	-	-	-	-	-	-	-	-	
06/10/90	26/09/90	K391	33762	15.9	.1	0	.4	1.9	0	0	0	.2	0	0	0	0	0	1.3	0	0	0	1	-	-	-	-	-	-	-	-	
11/10/90	09/10/90	K675	33807	16.9	.1	0	.5	2	.4	0	0	.4	0	0	1	0	0	1.3	0	0	0	.9	-	-	-	-	-	-	-	-	
19/10/90	12/10/90	K1204	33852	14.4	0	0	1.1	1.9	0	0	0	.2	0	0	1	0	0	1.3	0	0	0	.7	-	-	-	-	-	-	-	-	
29/10/90	24/10/90	K1738	33895	17.6	.1	0	1.5	2.2	0	0	0	.3	0	0	0	0	0	1.2	0	0	0	.8	-	-	-	-	-	-	-	-	
09/11/90	07/11/90	L502	33939	20.4	.2	0	.5	2.3	.4	0	0	.4	0	0	2	0	0	1.4	0	0	0	.8	-	-	-	-	-	-	-	-	
24/11/90	22/11/90	L1443	33985	18.9	.1	0	1	2.4	.6	0	0	.5	0	0	2	0	0	1.4	0	0	0	.9	-	-	-	-	-	-	-	-	
06/12/90	03/12/90	M315	-----	18.6	0	0	.5	2.3	.4	0	0	.3	0	0	0	0	0	1.5	0	0	0	.8	-	-	-	-	-	-	-	-	
06/12/90	03/12/90	M344	34029	19	.1	0	.6	2.4	0	0	0	.4	0	0	2	0	0	1.5	0	0	0	.8	-	-	-	-	-	-	-	-	
23/12/90	16/12/90	M1176	34073	17.4	.2	0	.5	2.1	.4	0	0	.4	0	0	1	0	0	1.2	0	0	0	.6	-	-	-	-	-	-	-	-	
03/01/91	28/12/90	A202	34113	17.9	.2	0	.5	2	0	0	0	.4	0	0	0	0	0	1.3	0	0	0	.7	-	-	-	-	-	-	-	-	
14/01/91	11/01/91	A826	34178	19.3	.2	0	.6	2.2	.4	0	.1	.4	0	0	1	0	0	.9	0	0	0	.8	-	-	-	-	-	-	-	-	
24/01/91	21/01/91	A1505	34816	19.2	.2	0	1	2.1	.4	0	0	.4	0	0	0	0	0	1.5	0	0	0	.8	-	-	-	-	-	-	-	-	
04/02/91	01/02/91	B164	34251	20.2	.2	0	.5	2	0	0	0	.4	0	0	0	0	0	1.1	0	0	0	.8	-	-	-	-	-	-	-	-	
06/02/91	04/02/91	B418	34258	19.5	.2	0	.7	2.1	.4	0	0	.4	0	0	0	0	0	1.1	0	0	0	.8	-	-	-	-	-	-	-	-	
20/02/91	18/02/91	B1129	34295	14.8	.1	0	.5	1.7	.3	0	0	.3	0	0	1	0	0	.7	0	0	0	.6	-	-	-	-	-	-	-	-	
Change on 21/02/91				Removed :- A14-970									Reason :- Timex for overhaul.																		
10/05/91		E479	-----	4	0	0	.2	.6	0	0	0	.2	0	.4	0	0	0	1.1	0	0	0	.5	-	-	-	-	-	-	-	-	
16/05/91	14/05/91	E813	34362	4.5	0	0	.4	.7	.3	0	0	.2	0	.4	0	0	0	1.3	0	0	0	.6	-	-	-	-	-	-	-	-	
25/05/91	23/05/91	E1321	34405	6.2	0	0	1.2	.9	.6	0	0	.1	0	.6	1	0	0	1.8	0	0	0	.8	-	-	-	-	-	-	-	-	
06/06/91	04/06/91	F310	34448	2.6	0	0	.5	.4	.2	0	0	.1	0	.2	0	0	0	.8	0	0	0	.4	-	-	-	-	-	-	-	-	
20/06/91	17/06/91	F1054	34495	6.5	0	0	.2	.8	.4	0	0	.1	0	.7	0	0	0	1.9	0	0	0	.8	-	-	-	-	-	-	-	-	
01/07/91	27/06/91	G014	34539	7.3	0	0	.7	.9	.3	0	0	.1	0	.7	0	0	0	2.3	0	0	0	.8	-	-	-	-	-	-	-	-	
13/07/91	11/07/91	G817	34584	8.2	0	0	1.1	.9	.3	0	0	.1	0	.9	1	0	0	2.7	0	0	0	.7	-	-	-	-	-	-	-	-	
13/07/91	11/07/91	G818	34584	8.2	0	0	1.1	.9	.3	0	0	.1	0	.9	1	0	0	2.7	0	0	0	.7	-								
25/07/91	23/07/91	G1471	34625	8.4	0	0	.6	.9	.4	0	0	.2	.1	.8	0	0	0	2.9	0	0	0	.8	-								
07/08/91	05/08/91	H312	34666	8.4	0	0	1	.9	.6	0	0	.2	.1	.8	0	0	0	2.9	0	0	0	.8	-								
20/08/91	16/08/91	H1034	34707	10	0	0	.8	1.1	0	0	0	.1	.1	1	0	0	0	3.7	0	0	0	.9	-	-	-	-	-	-	-	-	
31/08/91	29/08/91	H1645	34752	10.9	.1	0	2%	1.2	1%	0	0	.2	.1	1	0	0	0	3.9	0	0	0	.9	-	-	-	-	-	-	-	-	R.O.C
12/09/91	10/09/91	J572	34798	8.7	0	0	1	1	.5	0	0	.2	0	.8	0	0	0	3.1	0	0	0	.8	-	-	-	-	-	-	-	-	
28/09/91	24/09/91	J1478	34842	13.1	.1	0	1.5	1.4	.4	0	0	.2	.1	1.5	1	0	0	4.9%	0	0	0	.8	-	-	-	-	-	-	-	-	R.O.C
09/10/91	06/10/91	K541	34887	12.5	.1	0	2.2	1.3	1	0	.1	.3	.1	1.3	0	0	0	4.9	0	0	0	.9	-	-	-	-	-	-	-	-	
18/10/91	16/10/91	K1024	34931	13.3	.1	0	1.6	1.4	1.1	0	.1	.3	0	1.3	0	0	0	5.1!	0	0	0	.9	-	-	-	-	-	-	-	-	ALERT
29/10/91	26/10/91	K1586	34975	14	.1	0	2.2	1.6	.6	0	0	.2	.1	1.4	0	0	0	5.6!	0	0	0	.8	-	-	-	-	-	-	-	-	ALERT
08/11/91	06/11/91	L408	35018	15.2	.1	0	2.3	1.8	.8	0	.1	.2	.1	1.6	1	0	0	6.2!	0	0	0	.8	-	-	-	-	-	-	-	-	ALERT
26/11/91	20/11/91	L1221	35062	16.1	.2	0	1.9	2.1	.7	0	.1	.3	.1	1.8	0	0	0	6.3!	0	0	0	.7	-	-	-	-	-	-	-	-	ALERT

Main Gearbox A14-974

RUN DATE 06-12-1991 File 3

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FIGURE 5.12 : SOAP data - gearbox 974 in aircraft G-BEIC

6.0 USE OF HUMS DATA

This section discusses the use of HUM data to ensure that aircraft airworthiness is maintained. The process begins with the presentation of the data, this must then be assessed and any necessary decisions taken. The integration of HUMS technology into BIHL's current operational structures is also discussed. Finally, to maximise operational benefits from HUMS, it is necessary to consider the use of the data for maintenance credits.

6.1 Presentation of data

Data is presented to the engineers and ground crew at two levels:

(a) **DRU display to mechanics and engineers on the flight line**

This data is intended to be used as a 'go/no go' report and, as such, it is currently presented as simple messages such as 'no exceedances' or 'gearbox vibration exceedance has occurred'. When the first message is presented, a decision can be made to clear the aircraft for further flight. If an exceedance is recorded, however, it is necessary to transfer the data into the GSC for interpretation before a further decision is made. This is designed to fit in with operational procedures where the decision to ground an aircraft would be taken at a higher level.

The production DRU offers menu options for the display of more detailed information on the results downloaded from the airborne system.

(b) **GSC display to licenced engineers at the maintenance base**

The method of data presentation on the trial GSC will be carried over to the production system, this is mainly graphical in form. The presentation is such that the behavior of the various parameters can be understood by the licenced engineer and warning indications clearly identified and located. Minor amendments to the screen displays made in the production GSC with further improve useability.

6.2 Assessment of HUM data and decision taking

Once the HUM data has been presented to operational staff it must be assessed to determine the airworthiness of an aircraft, and action taken when there are indications that this is being compromised by component damage.

From a flight safety point of view, the objective for HUMS is to obtain the maximum airworthiness benefits with the minimum of operational penalties in terms of system support costs. The goal is to fully integrate the HUMS into existing aircraft operational, maintenance and safety assessment procedures. Some of the following steps will be required on the route to achieving this goal:

(a) To provide robust diagnostics for each new aircraft type HUMS data must be reviewed to ensure that this behaves in the same manner as on rig trials and other transmission types. Much of the trial experience has been gained on a single S-61 aircraft. It is envisaged that experience will be assessed over a period of time, reviewing data from a number of aircraft of each of the different types fitted with HUMS.

(b) There should be a two way transfer of experience and information between SHL and BIHL. As data accumulates SHL can refine recommendations on HUM data interpretation to enable BIHL to define safety decisions based on HUM system indications. The data assessment process must be acceptable to operational staff and be clearly understood.

(c) There needs to be a dissemination of information and experience within BIHL such that the licenced engineers who are nominated to be HUM system users receive training in data assessment and the actions which must be taken based on this.

(d) It is important that aircraft manufacturers are included in the process of reviewing experience gained with HUM systems. Informative gearbox strip reports would provide valuable information to assist in interpreting the HUMS data in terms of component damage. Furthermore, HUM experience should be shared with manufacturers with the objective of obtaining their recognition of the validity of the applied health monitoring techniques and of gearbox rejection limits based on these.

It must be understood that different health monitoring techniques can be complimentary, this is particularly the case for vibration monitoring and oil and debris analysis. The different techniques can detect different types of damage, but neither technique can detect all types of damage. In a situation where traditional monitoring methods reinforced with years of experience, ie SOAP, debris in filters or on chip detectors, were to indicate an apparent problem which vibration analysis for some reason had not detected, it must be assumed that the damage or defect is of a nature which is not detectable by vibration analysis, and an investigation into the problem carried out.

BIHL believe that the problem is more likely to arise in the other direction, that of acting on results from the new techniques where traditional monitoring methods are not responding to a fault. The engineers who are to be faced with the problems of data assessment must have sufficient depth of training and confidence in themselves and the system before they can make a decision of accepting or rejecting a component.

The first rejection of a gearbox based on HUMS data where no mandatory requirements are in force, perhaps without corroboration from another monitoring technique, will be a difficult decision and may well have significant financial implications, particularly on a Power by the Hour unit. The functional credibility of the system must, therefore, be established with aircraft manufacturers and operators alike. Detailed briefings to manufacturers and operators regarding the operating principles and analysis results obtained may be necessary to fulfill this requirement.

6.3 Integration of HUMS into organisational structure

The implementation of HUMS is expected to require minor changes to BIHL's existing engineering structure. BIHL's initial ideas for application of this new technology might require a structure along the lines of that shown in Figure 6.1. The reporting chain stays within the existing engineering structure, and introduces a new position, HUMS Engineer.

The HUMS engineer will be the company point of contact for external oil analysis services and could control an in-house operation using an oil debris particle quantifier, should this be required. The HUMS engineer will also be BIHL's point of contact with SHL. It is inevitable that, for some time after the FDR/HUMS enters service, there will be a requirement for expert assistance with interpretation of data which lies outside established rejection criteria.

Each operating base will be provisioned with a Ground Station Computer (GSC), into which the HUMS data for the base aircraft will be transferred and subsequently monitored by the line level engineers. As the licenced engineer is responsible for the aircraft under his charge, he should have access to all the information available relating to the serviceability of those aircraft. It is BIHL's objective that the line level engineers will perform the tasks of operating the system and assessing the data. All users of the GSC will be individuals nominated by BIHL who have received training in these tasks.

A strategy of data assessment on site by the base staff was adopted as an objective. Figure 6.2 illustrates the operational interface and decision chain which it is envisaged will be established. Company procedures will be defined for all reporting and decision making activities. Rejection criteria should be established as a series of instructions and clear executive commands which leave as little as possible to personal judgement. It will require some accumulation of service experience before such clear instructions can be fully established.

The task of data transfer from the airborne system to the DRU can be readily written into existing procedures for post-flight servicing. As the DRU is able to give an immediate indication of fitness for further flight, a check of this will be made at the flight line. The aircraft will either be cleared for flight or a report made to a licenced engineer if an exceedance has been recorded.

On detection of an exceedance, the decision to ground the aircraft will be made by the Licenced Engineer/Shift Supervisor. Responsibility for component rejection, due to the significant financial implications, will be vested in the Base Engineer. The HUMS Engineer will provide overall support to the bases and be the central point for collating all experience gained form HUMS.

6.4 Maintenance credit

There are two basic areas where HUMS offers potential for future maintenance credits. The first area, possibly offering the first benefits, is that of carrying out (perhaps automatically) maintenance checks which are currently performed manually with portable equipment. Examples are oil cooler fan balance checks, engine input shaft balance checks, main rotor track and balance and tail rotor balance checks. The second area is the possibility of enabling an extension of current component in-service lives.

In both of these areas it is essential that aircraft constructors are involved in process of identifying and obtaining maintenance credits. It will be the constructors responsibility to define the health monitoring requirements based on a Failure Modes, Effects and Criticality Analysis (FMECA) to ensure that component integrity is properly maintained with any extension of in-service periods.

For award of maintenance credit towards extending overhaul lives of HUMS monitored components, it is anticipated by BIHL that the basic principles established in the fixed wing world for large turbine engines, of vibration monitoring and oil analysis over an extended period, will be applied.

This suggests that it will be necessary to collate HUMS data on a fleetwide basis over a considerable period of time. It is important that accurate records are kept, the linking of data with gearbox serial number and operating hours in the GSC is a valuable aid to this. In addition an oil analysis programme may be required fleet wide, BIHL is carrying out an active oil and debris analysis programme at present.

Archived data from the production HUMS will be in the form of tape backups, produced at regular intervals from each base GSC. Control, collation, and fleet wide long term trend monitoring of this data will be the responsibility of the HUMS engineer.

A Maintenance Credit Working Group has been formed under the guidance of the CAA. The activities of the Group are directed towards developing the application of HUMS type data to maintenance credit. BIHL is participating fully in the activities of the Group.

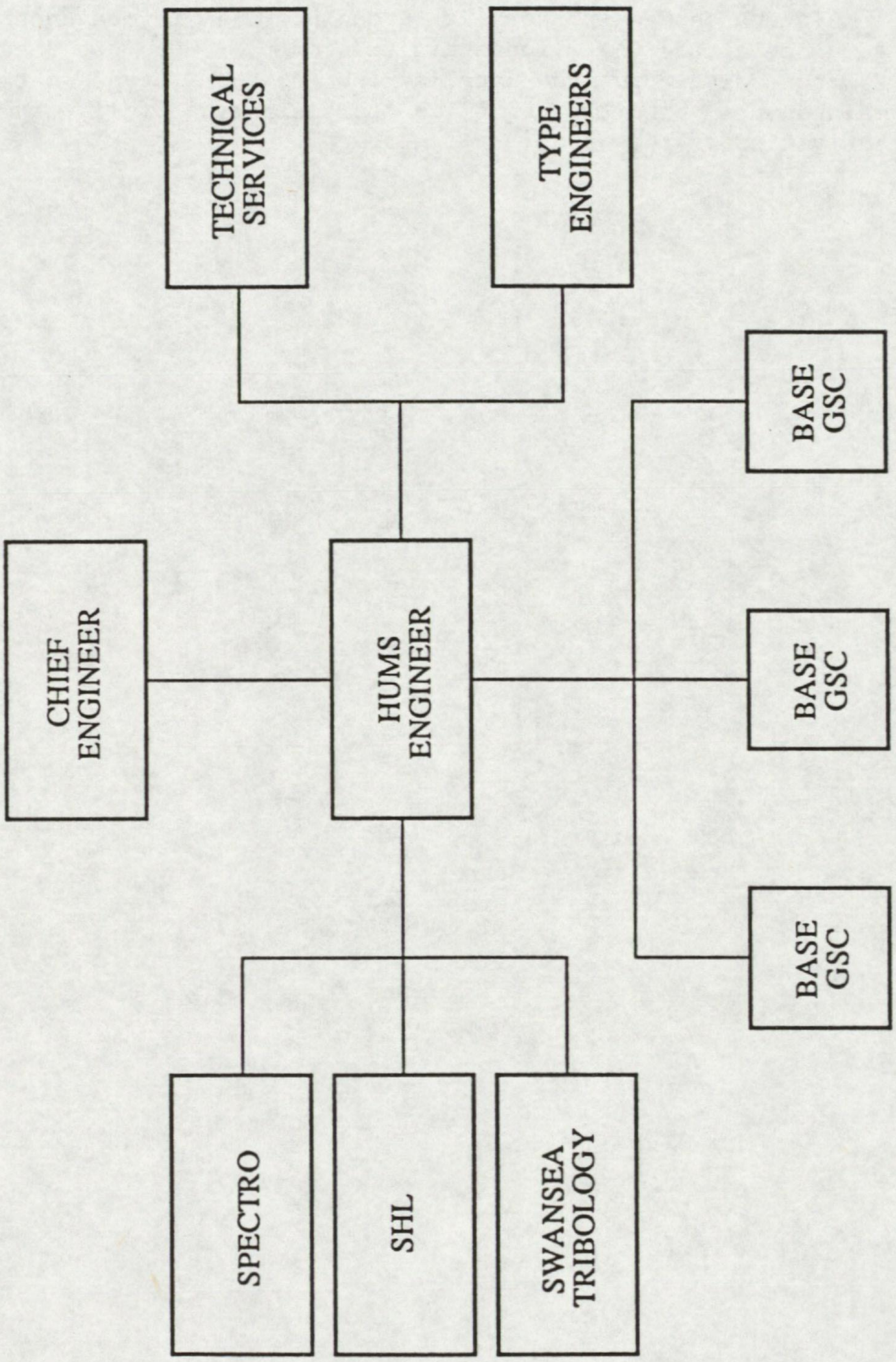

FIGURE 6.1 : Overall organisational structure for HUMS

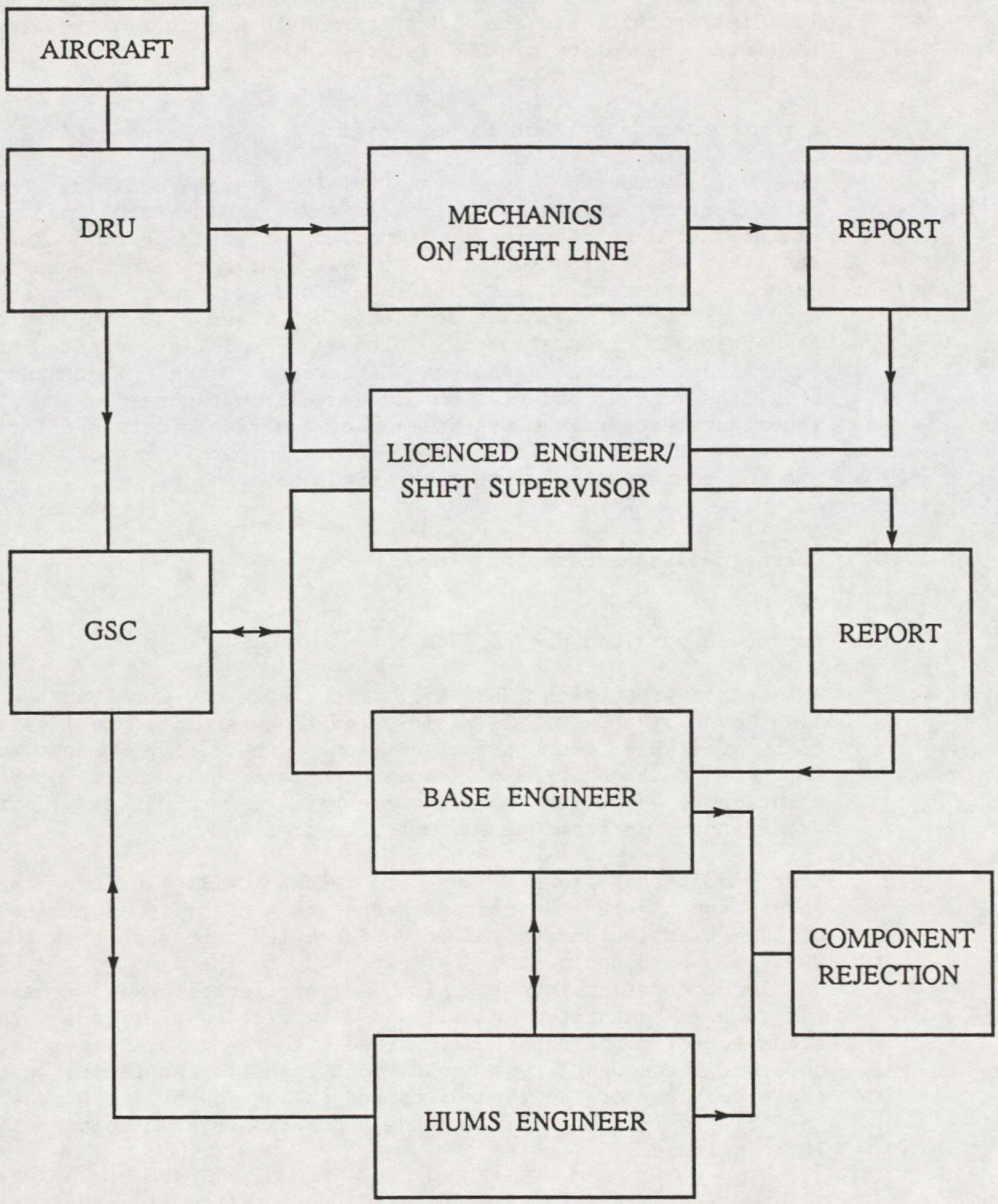

FIGURE 6.2 : HUMS operational interface and decision chain

7.0 DISCUSSION

This section discusses some issues which go beyond the immediate results of the HUM trial and look more look towards the future operation of HUM systems.

7.1 Airworthiness contribution potential

The data produced by the trial system confirms the participating companies beliefs that HUMS can make a significant contribution to improved airworthiness. This contribution is expected to grow as further experience is gained. However, no two failure modes are exactly the same and in a number of cases accidents have been attributable to 'exceptional' circumstances. Although HUMS is expected to significantly increase failure detection, some failures may still be missed due to unforseen circumstances. It is important that maximum use is made of experience obtained from operating HUM systems to ensure lessons learnt from experience are incorporated in future generations of systems.

7.2 Operational considerations for HUM systems

7.2.1 *Impact on workload due to HUMS*

Although a production HUMS will impose some new work tasks on line level staff, it is anticipated that benefits are likely to be available from the automation of repetitive, manpower intensive tasks such as oil cooler and rotor balancing. Other maintenance benefits include accurate recording of limit exceedances, performance and usage information.

Some additional tasks due to HUMS will include the inspection and test of units and sensors and the routine tasks of data transfer and assessment. Scheduled maintenance on the HUMS/FDR airborne system is expected to be small. The workload of defect investigation and rectification will remain an unknown quantity until in service experience is accumulated. The experience gained with the trial system is, however, encouraging in that most installation faults were cable problems of the type discussed in Section 5.2. Greater reliability is expected from the production system components in this respect.

If HUMS installation becomes mandatory, it will perhaps be regarded as a Minimum Equipment List (MEL) item. As such, there will be restrictions placed on operation of the aircraft with the system unserviceable. If based upon the requirements for the current CVR, this will restrict the flying permitted with an unserviceable system, and prohibit take-off from bases where BIHL staff may be expected to be available to carry out rectification. As a consequence a programme of avionics engineering training is likely to be required in order to establish the degree of knowledge needed to rectify problems promptly, and to have sufficient avionic licence cover available for certification.

7.2.2 *Impact on stores system*

Production system components will pass through the established stores procedures, be allocated stores locations and will be issued, recorded and controlled in the same manner as all other aircraft components. The impact of the HUMS/FDR on the BIHL stores system and procedures is expected to be minimal.

Spares backup for the system will have to be sufficient to preclude the situation arising where, due to a HUM system becoming unserviceable, an aircraft is grounded due to spares not being available. Stores holdings will have to be reviewed in the light of operational experience.

7.2.3 *Additional weight of HUMS capability*

The S61 trials HUM system weighed a total of 84 lbs, a Fairchild CVR weighing 25 lbs was also carried on the trials aircraft (the CVR is currently fitted in all BIHL aircraft). The integrated HUMS FDR/CVR to be installed in the S61 weighs a total of approximately 72 lbs. The difference in weight between a standard CVR/FDR and a system incorporating the HUMS functions is small.

7.2.4 *Independence from GSC*

An obvious benefit of in-flight processing of HUMS data is that results from the system are available immediately after shutdown, with the aircraft still on the flight line. The DRU is required to initially read and display the results, and perform transfer of the results to the GSC. This will permit a rapid aircraft turnround, essential for a busy operation and possibly difficult to achieve if it is necessary to process data from each aircraft in turn through a ground based system.

In a short term detachment away from the main base a DRU, with its capability to store multiple data downloads, is all that will be required in terms of additional support equipment for a HUMS equipped aircraft. Oil sampling from offshore installations has been tested in the past by BIHL, imparting a delay of perhaps an extra day over samples sent from an established base. Samples are sent from the operation to the laboratory, with results going directly to the main base where they may be compared with fleet standards.

To provide historical trend data, or in a situation where detachments from established bases are a regular operational requirement, a portable (lap-top) computer may be readily configured as a GSC.

7.2.5 *Visiting aircraft*

Data from a HUMS aircraft can only be transferred into a GSC when the GSC has the database for that particular aircraft within its memory. The situation could arise of a BIHL aircraft unexpectedly visiting another base, eg an Aberdeen Puma staging through Sumburgh, perhaps diverted due to weather or unserviceability. The individual aircraft databases will be held at the relevant home base therefore, although the aircraft HUMS data could be checked using a DRU, the data could not be stored in the GSC.

When maintenance credits are established, they may be invalidated if too many sets of results are lost in situations such as this. To prevent loss of data a temporary aircraft database could be set up on the host base GSC, and then 'exported' when the aircraft returns to its normal base. This capability was incorporated in the trial GSC and the operation is quite simple to perform.

7.3 In-flight warning

In-flight processing of gearbox vibration data offers the potential for providing in-flight warnings. Any system providing this capability must offer:

1 Reliability which is fail-safe. A ditching in severe sea conditions as a result of a spurious HUMS warning arising from a system fault could result in loss of life and the aircraft.

2 The longest possible advance warning. Helicopters in current North Sea operations are rarely more than 1 hour from land, if not from an airfield. There are also many offshore installations and ships available for an emergency landing. A fault detection capability which provides sufficient warning to make landfall or an offshore diversion is preferable to a few minutes of warning which may commit a crew to a ditching.

3 A primary warning system function, categorised in degree by the scale of actions required by the crew. Defect indication to the crew should not advise the exact nature of the fault unless a pilot action to reduce the immediate danger (eg engine shutdown in event of a fault in an input section) is an available option. Information overload to the crew in a situation of severe stress should be avoided.

4 An extremely low probability of generating false alarms, which can be verified by experience of ground based warning systems over a significant period of time.

7.4 Analysis techniques not demonstrated in the trial

This section comments on some vibration analysis techniques which were initially intended to be included in the CAA trial HUMS, but which had not been demonstrated by the end of the trial.

(1) Gear analysis indicator FM5

It was originally planned that the FM5 indicator would be included in the gear analysis suite in the trial HUM system. The FM5 indicator was developed to assist the detection of localised tooth damage on epicyclic gears. It is still believed that FM5 can provide some increase in detection sensitivity for early localised tooth damage and it is hoped that the technique can be incorporated in a future HUM system.

(2) Bearing analysis

Rolling element bearing analysis was also initially intended to be included in the CAA trial HUMS. For oil washed bearings inside a gearbox there is an overlap in the fault detection capability of vibration monitoring and oil debris monitoring.

Rolling element bearing analysis could offer most airworthiness benefits when used to monitor external bearings which currently have no on-line health monitoring. Such bearings may include tail drive shaft bearings, any exposed main rotor shaft bearings, swashplate bearings and tail rotor pitch change bearings. Again it is hoped that bearing analysis will be included in a future HUM system.

(3) Rotor track and balance

The rotor track and balance function was implemented in the CAA trials HUM system but, owing to commissioning problems, could not be satisfactorily demonstrated before the end of the trial.

Rotor track and balance is seen as a key HUMS function, offering significant maintenance benefits and also the potential for some safety benefits. The function has been implemented in the production HUM system. The first S61 system is now operational and will provide an opportunity to gain the rotor track and balance experience which should have been obtained from the CAA trial.

7.5 Improvements incorporated in the production HUM system

A number of improvements have been incorporated in the production HUMS, several of these are the direct result of experience gained in the CAA trial.

Advantage has been taken of advances in hardware since the design of the CAA trial HUMS, and the fact that the HUMS is now integrated with an FDR. This has enabled a simplification of both the hardware and software incorporated in the airborne HUMS.

The implementation and control of the vibration primary analysis process has been improved, utilising the additional flight data required for the FDR. Accelerometer positioning, attachment methods, cabling and connectors have been improved, with additional accelerometers added to enable vibration monitoring of the tail rotor drive shaft and engines. The functionality of the production system has been increased.

Improvements to the production system hardware and software have significantly reduced the transmission monitoring cycle time. Results from the first S61 production HUMS indicate that enhancements made to the system have further increased the quality and stability of the vibration health monitoring data.

7.6 Future development of HUMS

The development of HUMS technology has largely been pioneered in the UK and the CAA HUMS trials have been carried out without the full involvement of aircraft constructors located in other countries.

To obtain the full airworthiness benefits of HUMS, aircraft constructors must play a major role in the future development of this technology. This involvement will be achieved through the UK CAA certification requirements for new aircraft types. Constructors will be responsible for (a) identifying health monitoring requirements on the basis of an FMECA, and (b) providing evidence to validate the effectiveness of selected techniques.

At present the majority of the aircraft constructors do not have sufficient expertise in transmission vibration analysis techniques to fully specify required techniques and algorithms. It is therefore important that HUM technology developers such as SHL work closely with aircraft constructors in the evolution of future HUM systems.

8.0 REFERENCES

[1] MAMR NO 0001 : 'Sikorsky Health Monitoring Trial', British International Helicopters, Issue 5, February 1989.