CIVIL AVIATION AUTHORITY

CAA PAPER 93003

HELICOPTER HEALTH MONITORING

Bristow Helicopters Ltd
– Operational Trial of Helicopter Health Monitoring Techniques

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This Paper presents the Bristow Helicopters Limited Precis of their Final Report (Ref No. BHL/HUM/1054A) on their Super Puma Operational Trial of Health Monitoring Techniques. This was one of two operational trials which were carried out between 1987 and 1991 as part of a helicopter safety research programme which was jointly funded by CAA, the UK Offshore Operators Association and the UK Departments of Transport and Energy (now HSE).

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

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FINAL REPORT
OPERATIONAL TRIAL OF HELICOPTER HEALTH MONITORING TECHNIQUES

1.0. INTRODUCTION

In December 1982 the Civil Aviation Authority (CAA) wrote to the Airworthiness Requirements Board (ARB) and suggested that the ARB review Helicopter Certification standards to ensure that they fully reflected the state of the art in terms of design philosophies, manufacturing techniques and availability of new materials.

The ARB convened a special group known as the Helicopter Airworthiness Review Panel (HARP) and their report (CAP 491) was published in June 1984.

The CAA then set up a working party "The Health Monitoring Working Group" to study the recommendations of the HARP report and to propose Airworthiness Requirements for future helicopters. This group published its report (CAA Paper 85012) in August 1985.

The CAA as part of its post HARP research programme contracted Bristow Helicopters Limited (BHL) to conduct an on-board helicopter health monitoring techniques trial, on a Bristows owned AS332L Super Puma helicopter based at Aberdeen Airport, Dyce, and to act as project managers for the trials programme on behalf of the CAA. This research programme was jointly funded by the Oil Industry, through the United Kingdom Offshore Operators Association (UKOOA), the CAA and the UK government - Department of Transport, and Department of Energy.

1.1. Scope

This document details the trials programme, hardware installations into helicopters, results and conclusions of an Operational Trial of Helicopter Health Monitoring Techniques.

1.2. Helicopter Type

There were up to five Aerospatiale AS332L Super Pumas involved at any one time in the trial.

1.3. Usage

The helicopters were operated on normal revenue services from Aberdeen Airport, including training and maintenance test flights, in the UK North Sea sector. Numerous dedicated trials test flights were also undertaken as considered necessary.

2.0. OBJECTIVE

The original BHL proposal stated the objective of the trial to be "to assess the suitability, reliability and capability of certain on board health monitoring techniques when applied to helicopters in operational service over the UK North Sea environment."

The following techniques were investigated:

a. Gearbox Vibration Analysis
b. Gearbox Oil Analysis (Off-Line)
c. Gearbox Quantity Debris Monitoring (On-Board)
d. Automatic Airframe Vibration Monitoring
e. Automatic In-Flight Rotor Tracking
f. Control Load Monitoring
g. Critical Temperature Monitoring
h. Control and Display System
i. Data Transfer System

3.0. PARTICIPANTS

The CAA contracted BHL to project manage the trial and to liaise with the large number of companies involved. See Figure 1.

3.1. Major Participants:

3.1.1. Bristow Helicopters Limited (BHL)

Responsible for the following:

- Trials management
- System integration and installation
- Test and Operational flying
- Trials Support and Data Analysis
- Reporting to the CAA

3.1.2. Smiths Industries Limited - Basingstoke (SI)

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

3.1.3. Westland Helicopters Limited (WHL)

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

3.1.4. M.J.A. Dynamics Limited

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

3.2. Minor Participants:

3.2.1. Stewart Hughes Limited (SHL)

Supply of main rotor blade tracking system.

3.2.2. Aerospatiale

Advice on trial equipment installation. Reports on strip examination of gearboxes.

3.2.3. Sensys

Supply of "FERROSCAN" oil debris monitoring system.

3.2.4. Endevco

Suppliers of gearbox and airframe accelerometers, advice on installation.

3.2. **Minor Participants:** (Cont.)

3.2.5. **Welwyn Strain Measurement**

Supply of strain gauges, advice on installation and training courses.

3.2.6. **Spectro Laboratories**

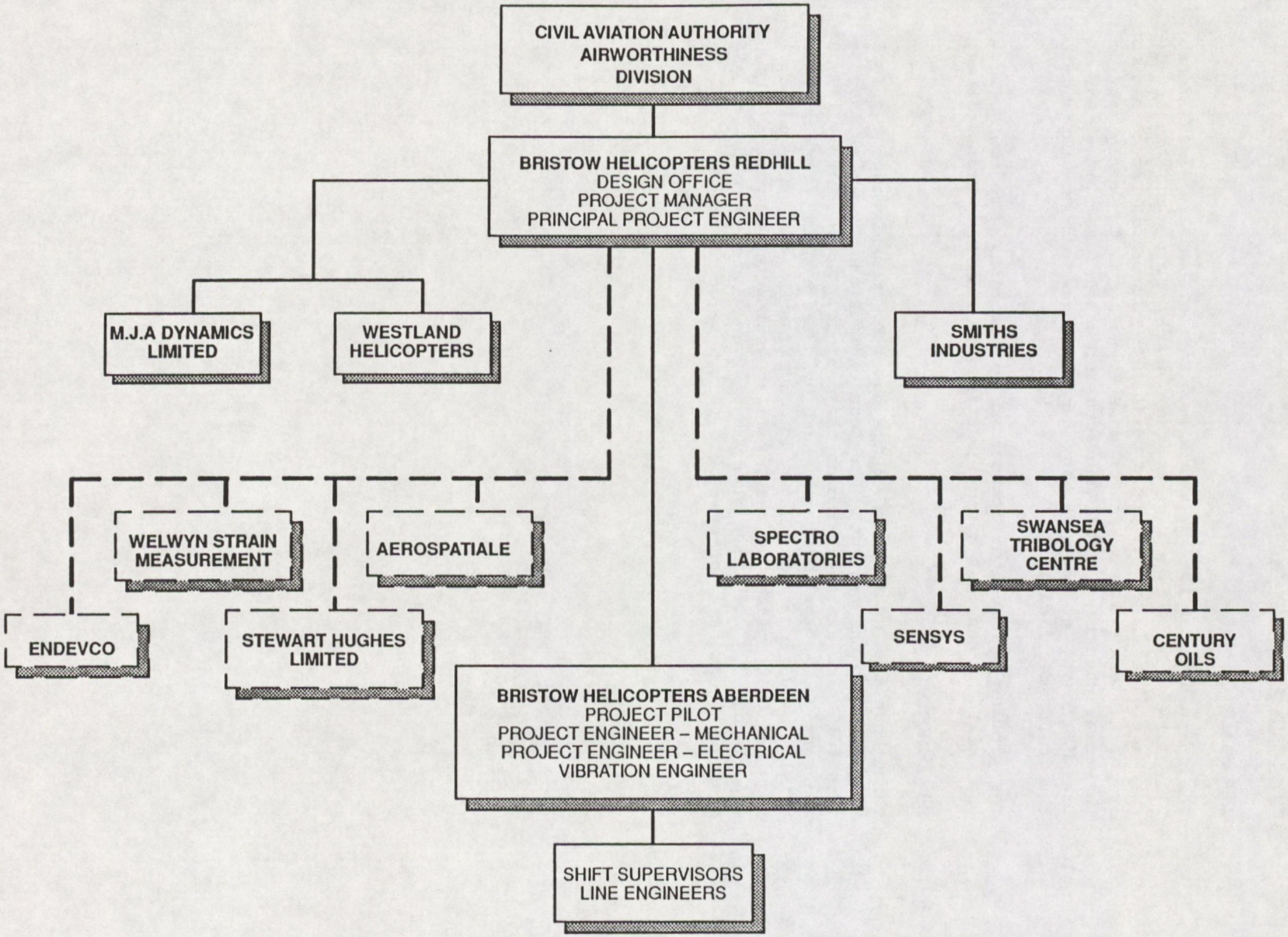
Oil debris analysis and Electron Microscope examination of wear particles.

3.2.7. **Swansea Tribology Centre**

Oil debris analysis and advice on tribology.

3.2.8. **Century Oils**

Oil debris analysis.



TRIALS MANAGEMENT

4.0. TIMESCALE AND BHL MANPOWER

4.1. Timescale

The start date of the programme was 1st October 1987 (see Figure 2). The trial lasted 36 months, nearly twice the originally estimated timescale. It would be fair to all parties concerned to state that there was a lack of understanding in the early part of the trial when the design/manufacturing was being implemented, of the difficulty of meeting very demanding objectives laid out in the draft specification.

The problem was further compounded by companies withdrawing from the trial and new ones being identified to fill the vacant places.

4.2. BHL Manpower

Throughout the entire trial there has been a minimum of two full time staff on the project. For long periods there were as many as five full time staff working on the project. Approximately 16,500 manhours will have been expended by the project team on this trial. BHL were not alone in under estimating the manhours required to complete the task, similar estimating errors have been experienced by all the other major contributors to the trial. Manhour figures are not available for these companies.

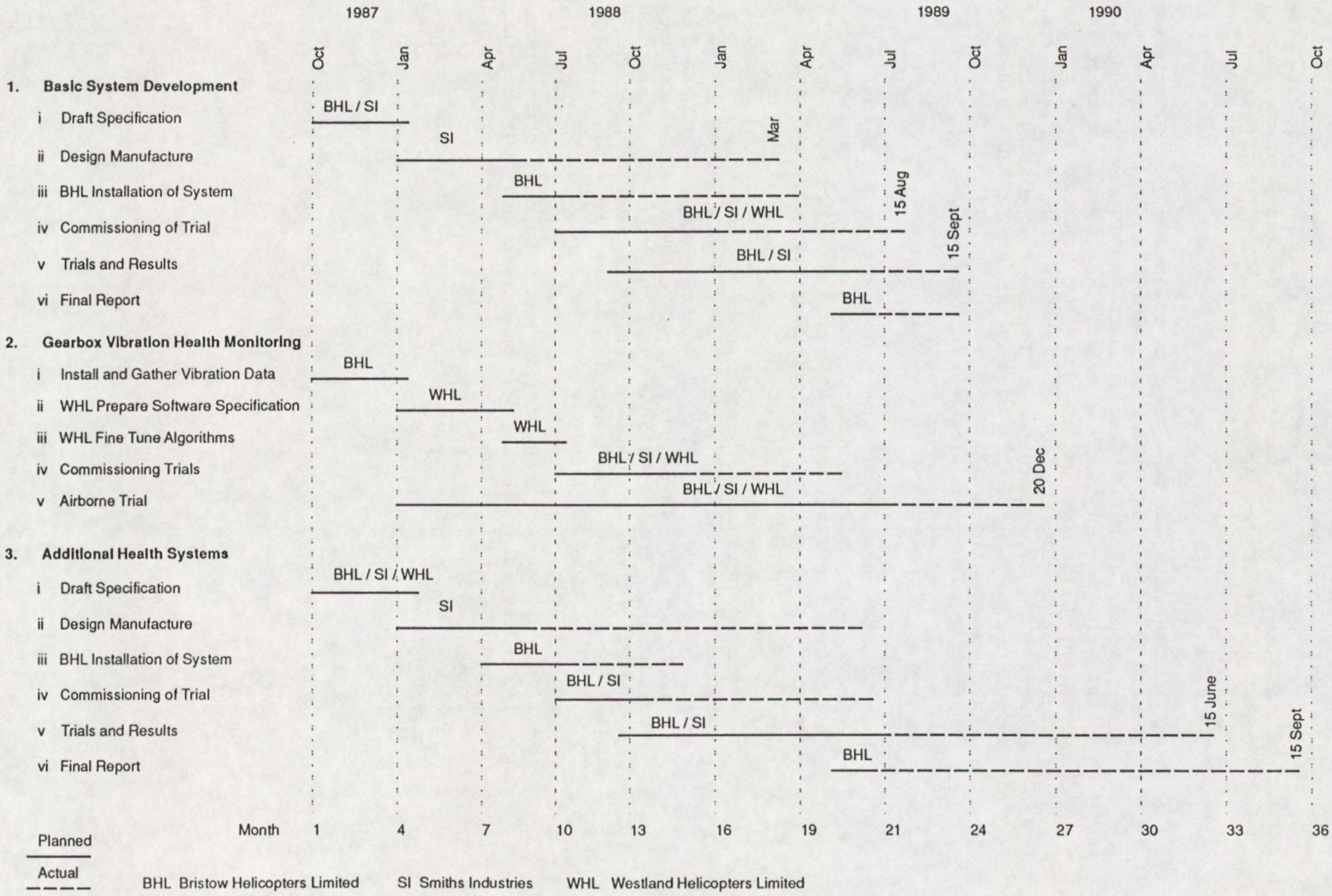

1987
1988
1989
1990
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
1. Basic System Development
i Draft Specification
BHL / SI
ii Design Manufacture
SI
Mar
iii BHL Installation of System
BHL
iv Commissioning of Trial
BHL / SI / WHL
15 Aug
v Trials and Results
BHL / SI
15 Sept
vi Final Report
BHL
2. Gearbox Vibration Health Monitoring
i Install and Gather Vibration Data
BHL
ii WHL Prepare Software Specification
WHL
iii WHL Fine Tune Algorithms
WHL
iv Commissioning Trials
BHL / SI / WHL
v Airborne Trial
BHL / SI / WHL
20 Dec
3. Additional Health Systems
i Draft Specification
BHL / SI / WHL
ii Design Manufacture
SI
iii BHL Installation of System
BHL
iv Commissioning of Trial
BHL / SI
v Trials and Results
BHL / SI
15 June
vi Final Report
BHL
15 Sept
Month
1
4
7
10
13
16
19
21
24
27
30
33
36
Planned
Actual
BHL Bristow Helicopters Limited
SI Smiths Industries
WHL Westland Helicopters Limited

FIGURE 2

5.0. DESCRIPTION OF THE TRIAL

The gathering of data was carried out in three distinct stages. The first two stages were used to gather gearbox vibration data only and the third stage made use of the Smiths Industries 0854 KEL computer, which was used to process data from various sensors described later in chapter 6.

5.1. Stage One

Whilst the design and development of the trials Health Monitoring System was in progress, it was decided to start collecting gearbox vibration data as soon as practicable. To this end, WHL supplied a TEAC analogue tape recorder to BHL in Aberdeen. Fitment and operation of the TEAC recorder was not practicable on revenue flights and so brief test flights were required to collect data. A total of 71 test flights were flown over an elapsed period of 6508 flying hours. Analysis of this data enabled WHL to develop algorithms specific to the Super Puma. A total of five AS332L (Super Puma) helicopters were used during stage one.

5.2. Stage Two

Stage Two saw the introduction of a SI Vibration Analysis System (VAS) to gather and analyse gearbox vibration data automatically. This allowed the algorithms to be evaluated whilst the SI 0854 KEL computer was being developed, thus providing a larger data base for diagnostic analysis.

The main item of hardware consisted of the VAS unit, which was installed in the passenger cabin. The unit was capable of remote control, allowing the pilot to initiate data acquisition as required during revenue flights. Following the experience obtained during stage 1, WHL were able to define the acquisition parameters as three (3) minutes of uninterrupted data taken during steady state flight conditions, i.e. in the cruise condition at 62% +/-2% (equally split) torque.

The VAS unit was a "portable" test set, originally designed for making ground based gearbox vibration measurements during a ground run, which was installed onto the helicopter for specific operational flights. The VAS unit consisted of a set of processing boards and a power supply interface module in a rugged carrying case.

5.2. **Stage Two** (Cont.)

The processing boards were capable of analysing the raw signals from the accelerometers and of producing and storing the following information:-

1. Signal Averaged data
2. M6* values (relates to gear damage signals)
3. Peak to Peak values
4. Standard Deviation
5. Shaft Eccentricity indicators
6. Gear Eccentricity indicators
7. Mesh Frequency Amplitude

After each flight the VAS unit was removed from the helicopter and connected to the ground based computer for downloading of the data. The ground based computer was supplied as part of the SI HUM package. The computer programme allowed the data to be stored, copied onto floppy diskettes for archiving and transfer to WHL, and for viewing the data.

During stage two, a total of 182 files of data were downloaded over a period of 4,400 flying hours. A total of five AS332Ls helicopters were used for this stage of the trial.

5.3. **Stage Three**

5.3.1. **Airborne System**

The first full airborne health monitoring system as detailed at Figure 3 was finally installed in a AS332L helicopter by January 1989, but it was not until June/July 1989 that most of the hardware/software problems were resolved and good quality data started to become available. See Figure 4 for sensor locations.

The Smiths Industries 0854 KEL HUM computer was contained in a half ATR (4 MCU) box and was installed in a cabinet in the cabin of the aircraft, together with the Stewart-Hughes RADS interface unit and BHL's interfaces for thermocouples, strain gauges, airframe accelerometers and computer downloading. A control and display unit was fitted in the centre console, and used by the pilot to initiate data acquisitions in flight. Data held in the S.I. 0854 KEL HUM computer was downloaded at the end of each days flying by plugging in a portable personal computer, which was programmed to act as a Data Transfer Unit (DTU).

The S.I. 0854 KEL computer was powered by 28V dc supply and cooling was by natural convection, conduction and radiation.

5.3.1. **Airborne System** (Cont.)

The following health monitoring data was stored in the S.I. 0854 KEL HUM computer:

i) Gearbox Vibration
ii) Main Rotor Track
iii) Airframe Vibration
iv) Strain Gauges and Thermocouples

The original concept was to have all the computation accomplished within the S.I. 0854 KEL HUM computer, but due to the lack of suitable equipment being available in the time-scales required, this was not achieved and the following extra items were introduced:

i) Stewart-Hughes RADS rotor blade tracker interface unit
ii) BHL interface unit

There were a total of three AS332L helicopters used during the third stage of the trials, but only two helicopters were equipped at any one time. The helicopters flew a total of 2,091 flying hours and some 283 data files were downloaded.

The oil debris monitoring system that was finally chosen was the Sensys Ferroscan which had a full flow 1" diameter sensor welded into the oil scavenge pipe and a electronics interface unit mounted in the HUMS equipment cabinet. This could not be included into the S.I. unit and therefore had to be installed as a stand. alone system.

The Ferroscan system was fitted to one helicopter for a total of 722 flying hours, during which time 67 files were downloaded.

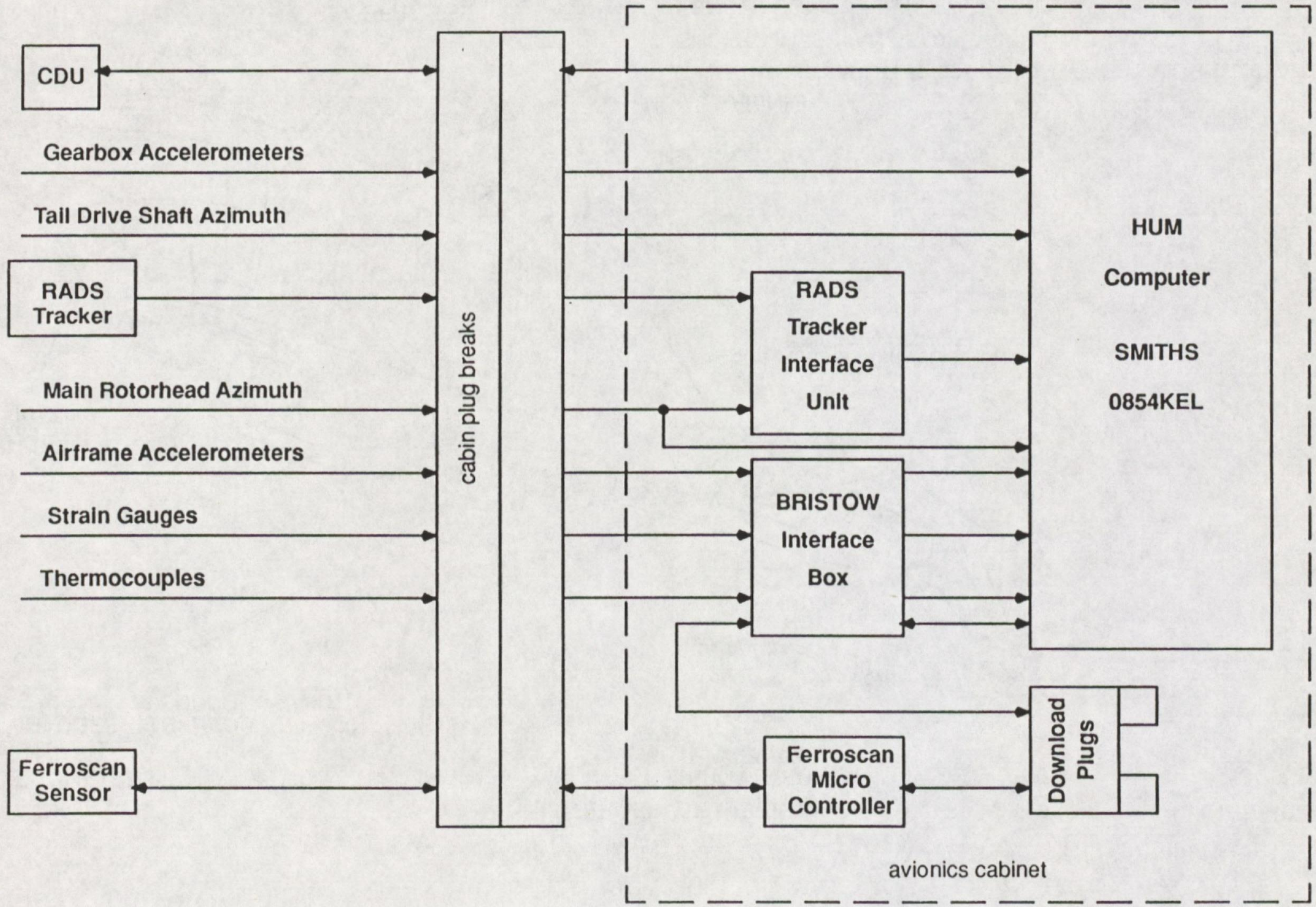
5.3.2 **Oil Sampling (Off Line)**

The oil sampling programme was operational from October 1988 to April 1990. Initially only Spectro Oil Limited and Swansea Tribology Centre were contracted by the CAA to analyse the oil from the main rotor gearbox with samples being taken approximately every 50 flying hours.

In April 1989 BHL introduced Century Oils Limited to the programme.

A total of 344 oil samples were despatched to the three oil companies and the various oil analysis techniques used were :-

i) Spectroscopic Oil Analysis Programme (SOAP).
ii) Particle Quantifier Analysis (PQ).
iii) Rotary Particle Depositer (RPD).
iv) General Oil Quality Tests.



AIRBORNE SYSTEM – Schematic

FIGURE 3

EQUIPMENT LOCATION AS332L

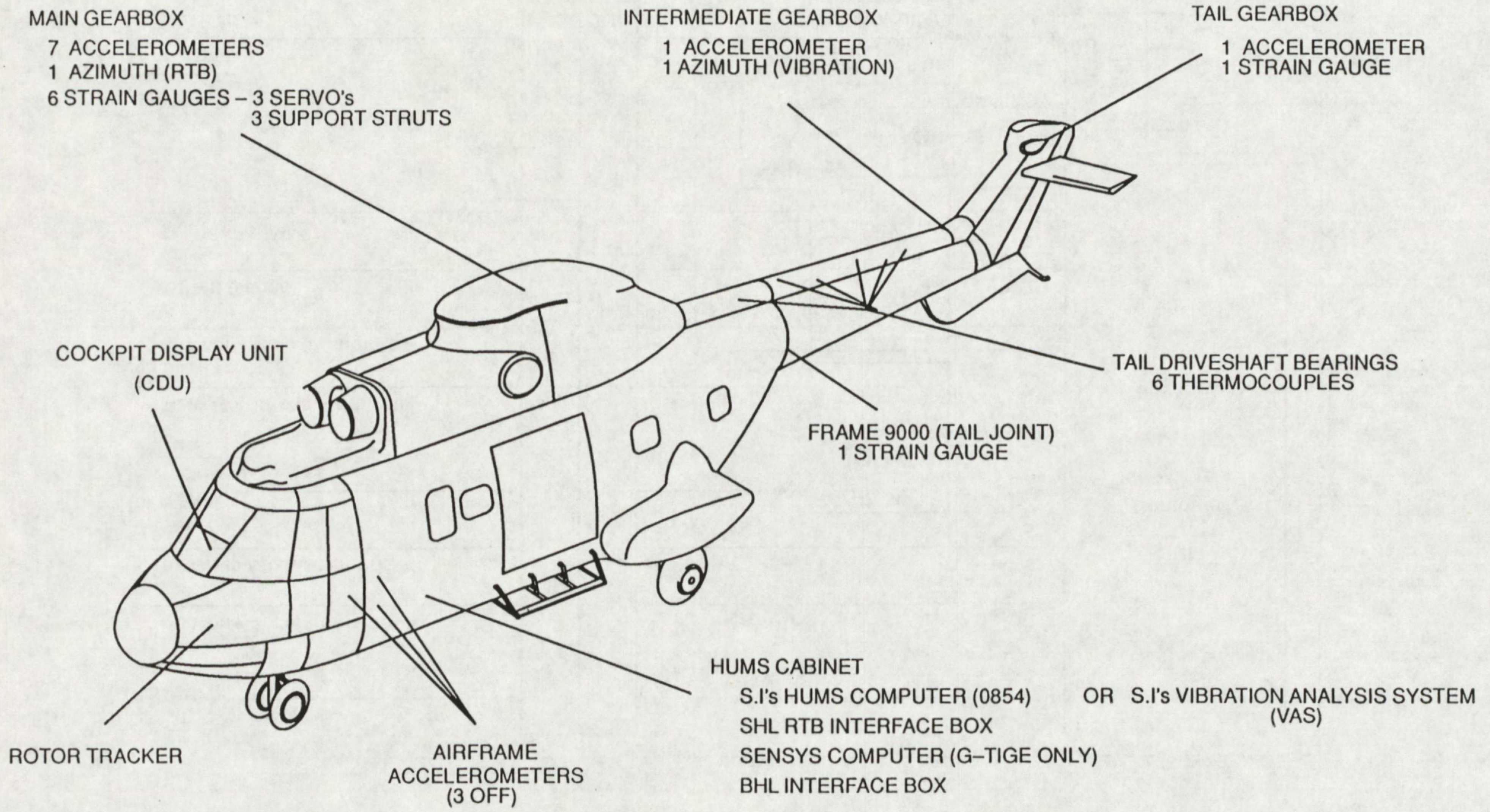


Figure 4

6. HEALTH MONITORING TECHNIQUES

6.1. Gearbox Vibration Monitoring

6.1.1. Introduction

This technique was based on the knowledge and experience built up by Westland Helicopters Limited (WHL) over many years of gearbox development and analysis. Their proposal split the trial into three distinct stages, allowing for development of the algorithms (specific to the Super Puma), flight testing, evaluation and subsequent inclusion of the algorithm into the Smiths Industries (SI 0854 KEL) HUM computer.

The technique takes the raw signals from accelerometers mounted on the particular gearbox being monitored and performs a number of calculations to average and enhance the signals so as to provide three quantative indicators relating to the health of each shaft and gear.

The indicators are M6*, peak to peak ratio, and standard deviation ratio. These indicators for a particular shaft are then related to each other in a three dimensional "Threshold Status Matrix" (Figure 5), following downloading to a ground based computer.

Twenty two shafts were monitored on the AS332L (Super Puma) helicopter using nine miniature accelerometers (Endevco model 7251-10), each securely mounted on the gearbox at positions defined by WHL.

The objectives of this part of the trial were:

i) To enable BHL to assess the feasibility of using both portable and on-board vibration health monitoring systems in an operational environment.

ii) To assess the performance of the WHL vibration health monitoring algorithms and parameters when applied to the Super Puma.

iii) To assess the reliability of the vibration health monitoring instrumentation and processing equipment.

iv) To make recommendations concerning the essential features of a vibration health monitoring system as part of a complete HUM system.

6.1.2. Aircraft Installation

Following a study of the Super Puma, nine accelerometer locations were chosen to monitor the condition of the transmission (Figure 6). Seven accelerometers were mounted on the main rotor gearbox (including three sited to monitor the two epicyclic gear reduction stages) and one each on the intermediate and tail rotor gearboxes. Signals from these, together with a speed reference signal (azimuth) taken from the intermediate gearbox input shaft, were fed via micro-dot cables to multi-pin connectors located in the rear cabin. The portable tape recorder used for data gathering during Stage I and II, the VAS and the 0854 KEL systems were powered and gathered vibration data via these connectors. The accelerometer locations and looming routes remained substantially unchanged throughout the trial.

6.1.3. Vibration Analysis Techniques

The WHL vibration analysis techniques incorporated in the S.I. VAS and 0854 KEL systems involve synchronous time averaging (signal averaging). Figure 7 shows the signal averaging process. The raw vibration data from the accelerometer is partitioned using an azimuth signal as timing reference into lengths corresponding to one revolution of a shaft of interest. Approximately 100 revolutions of the shaft are then summed as shown. This process causes the 'non-synchronous' information to be averaged out, leaving only vibration information from the shaft of interest. The output signal is called the signal average. The signal average is then processed further to highlight any gear tooth defects present. The frequency spectrum of the signal average is derived and certain parameters are computed from it. Predefined modifications are made to the frequency spectrum to suppress non-defect related frequencies and it is then transformed back into the time domain to produce an 'enhanced signal average'. Further health monitoring parameters are computed from the enhanced signal average.

The diagnostic capability of the signal averaging process is critically dependent upon the method of enhancement as well as upon the parameters and attendant thresholds that are subsequently applied.

M6*	PPR < X1		X1 = < PPR < X2		PPR > = X2	
	SDR < Y	SDR > = Y	SDR < Y	SDR > = Y	SDR < Y	SDR > = Y
LEVEL 1	G	A (D)	G	A (D)	A (L)	A (D)
LEVEL 2	G	A (L,D)	A (L,D)	A (L,D)	A (L)	A (L,D)
LEVEL 3	G	A (L,D)	A (L)	A (L,D)	R (L)	R (L,D)
LEVEL 4	A (L)	A (L,D)	R (L)	R (L,D)	R (L)	R (L,D)
LEVEL 5	R (L)	R (L,D)	R (L)	R (L,D)	R (L)	R (L,D)

Where :

Increasing LEVEL number indicates increasing value.

SDR – Standard Deviation Ratio

PPR – Peak to Peak Ratio

G Green Condition

A Amber Condition

R Red Condition

L Localized Defect

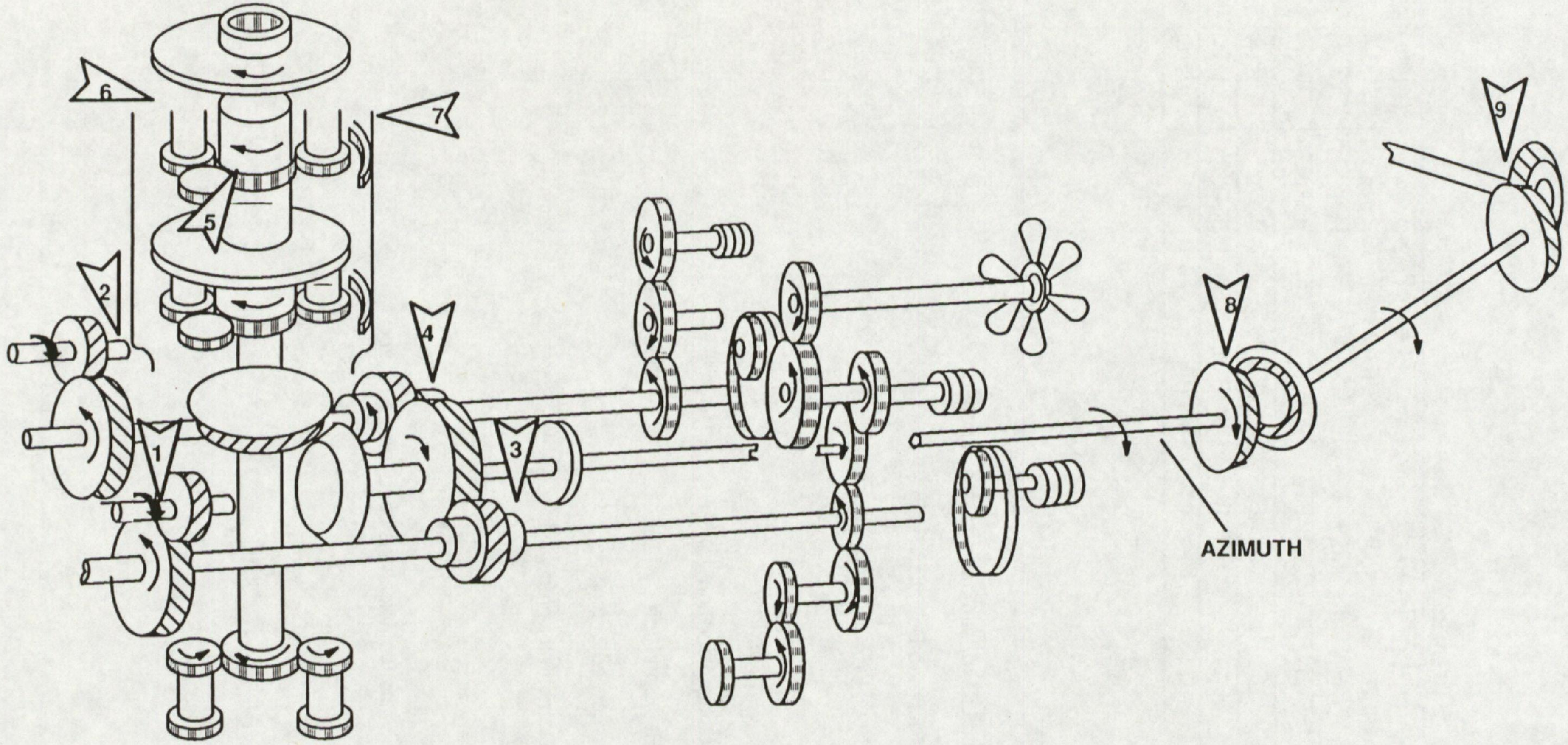
D Distributed Defect

LEVEL

$\left.\begin{array}{l} \text{x 1} \\ \text{x 2} \\ \text{Y} \end{array}\right\}$ Value for indications need to be specified

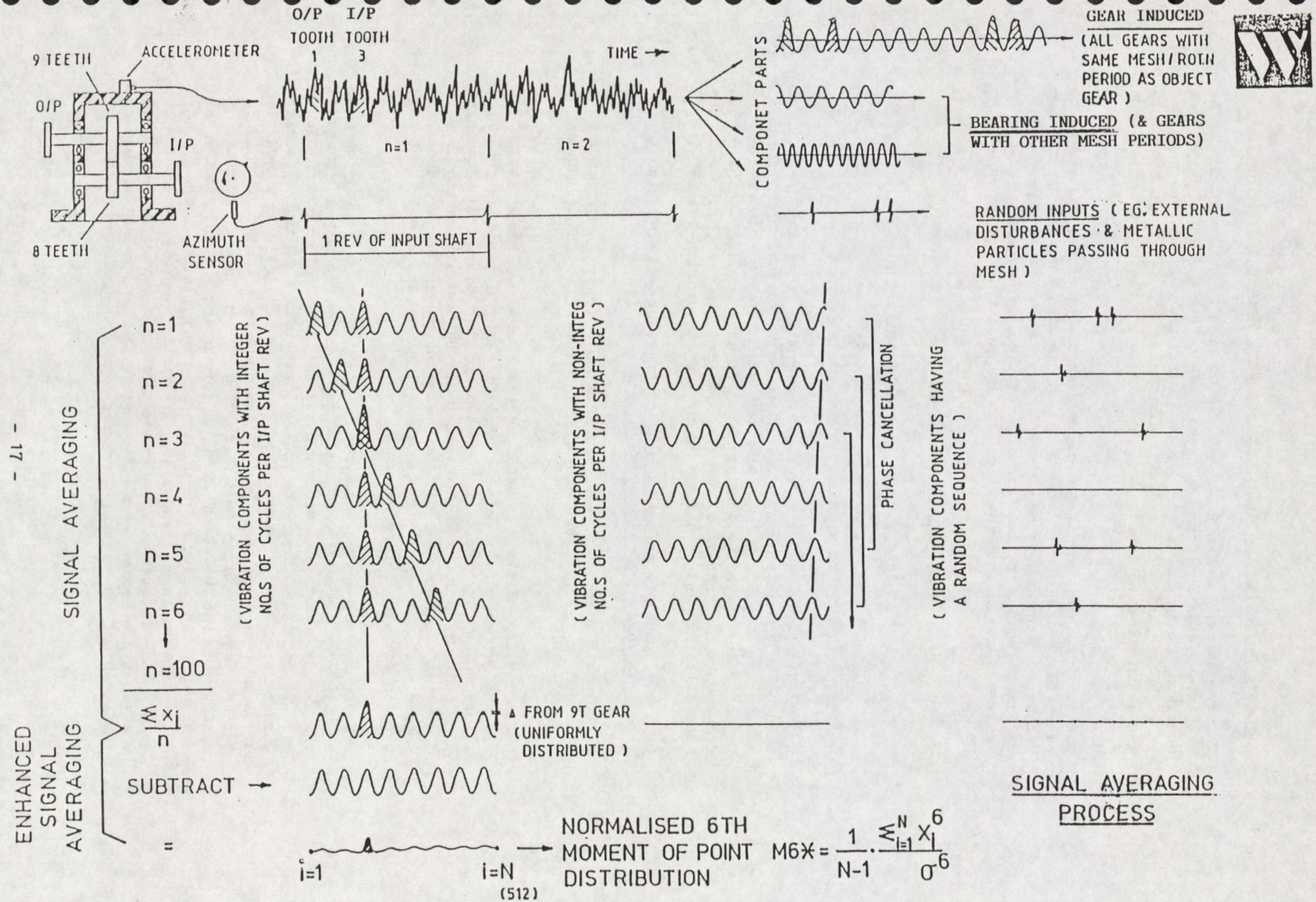
WHL GEARBOX FAULT MATRIX

FIGURE 5



AZIMUTH AND ACCELEROMETER LOCATIONS

FIGURE 6



WHL VIBRATION HEALTH MONITORING ANALYSIS PROCESS

FIGURE 7

6.1.4. Aircraft Operating Conditions During Data Sampling

Theory shows, and WHL's experience has confirmed that the vibration signals from a transmission are affected by their operating power condition. By implication any parameters computed from the vibration signals will also be affected. It is therefore WHL's practice to use a 'flight window' during the acquisition process.

During Stage I the range of aircraft operating regimes were assessed in order to find two flight windows, one ground and one flight, which could be conveniently achieved. These would desirably be within the normal operating regime of the aircraft and be suitable for vibration health monitoring purposes during Stage III.

The two power conditions chosen were:

Condition	Port Torque	Starboard Torque
Ground	10%	10%
Flight	31%	31%

As in-flight sampling was advantageous from an operational standpoint and this regime was shown to be suitable for vibration health monitoring, this operating condition was used for the majority of the VAS/0854 KEL trial. Ground sampling was only used for special transmission studies and as an aid to the identification and rectification of instrumentation faults.

6.1.5. Data Manipulation and Interpretation Procedures used during the trial (VAS/0845 KEL Stages II and III)

A schematic diagram of the manipulation of data from the VAS and 0845 KEL systems installed on the aircraft at BHL is shown in Figure 8.

On initiation of the vibration analysis process, the VAS/0845 KEL systems processes the data to produce a signal average, frequency spectrum, and enhanced signal average for each shaft together with their respective health monitoring parameters (section 5.2.). The signal averages and health monitoring parameters are stored in non-volatile memory. These are then downloaded to a ground station computer for assessment.

Primary assessment of gearbox condition was carried out at Aberdeen by comparing the health monitoring parameters stored in the download data header block against the fault matrix (Figure 5). If any thresholds were exceeded previously determined actions were carried out. The download data set, following the addition of maintenance related information, was despatched to WHL for further interrogation and archiving. WHL wrote software to manipulate the download data to produce plots of the signal averages. In addition, tables and trend plots of the primary parameters could be produced. An option was also available to carry out a statistical assessment of the parameter behaviour. The plots and tables were inspected by WHL to provide an 'expert' assessment of the transmission condition in support of BHL.

6.1.6. Technical Results

The following results relate to experiences with in-flight sampling at the aircraft power condition specified and subsequent analysis of the data at WHL for the period of Stage II, the VAS and 0845 KEL trial.

In general, instrumentation faults were identified by WHL after inspecting the processed vibration data and less frequently by BHL maintenance personnel at Aberdeen. WHL involvement was necessary in order to compensate for the lack of an adequate built in test system in the VAS/0854 KEL systems.

6.1.7. Samples Received at WHL

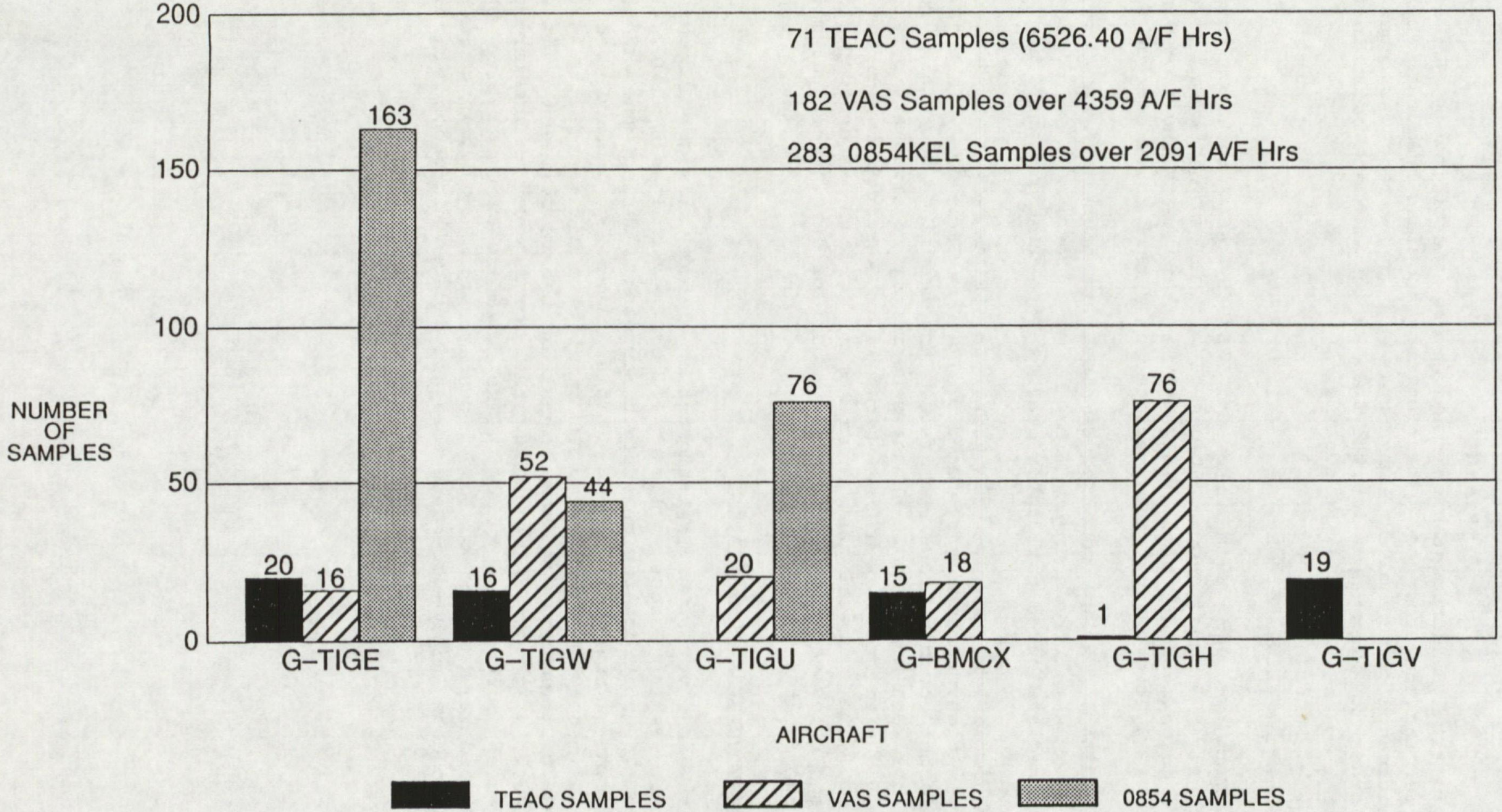
WHL received 465 valid in-flight VAS/0854 KEL vibration samples from five aircraft during Stages II and III of the trial. These were taken over a period of 6122:45 airframe hours and from 9 main rotor, 12 epicyclic, 8 intermediate and 7 tail rotor gearbox fits.

In addition 71 tape recorded samples were gathered over a period of 6526:40 airframe hours from 11 main rotor, 15 epicyclic, 8 intermediate and 8 tail rotor gearbox fits during Stage I and II.

The number of samples per aircraft (Figure 8) and the data acquisition/processing system are shown in Figure 9. In total 60 different combinations of main, intermediate and tail rotor gearbox were monitored. WHL have currently received strip reports for 10 main rotor gearboxes returned to Aerospatiale during the trial. These reveal that there was no evidence of any defects of direct relevance to the range of primary or development parameters or the fault matrix.

6.1.8. Instrumentation Reliability

There were very few instrumentation defect arisings during the trial. Taking Stages I, II and III of the trial as a whole, there were 26 instrumentation defect arisings during the 12649:25 airframe hours monitored. This gives a failure rate of approximately 1 fault per 4378 cumulative airframe hours. Only three of these arisings were caused by the removal and refit of a gearbox. It should be noted that there were no accelerometer failures during the trial. The instrumentation faults which occurred were traced to loose, contaminated (by oil or water) or disconnected micro-dot connectors and damaged micro-dot cables.



VIBRATION DATABASE

STAGE I, STAGE II AND STAGE III

Figure 8

6.1.9. Parameter and Fault Matrix Performance

During Stage III, 8844 shaft condition assessments were made using the fault matrix. There were no red alerts. There were 10 amber warnings during the trial. On closer interrogation of the maintenance records, the four cases associated with one shaft were found to be caused by the failure to redatum the PK-PK*(R) and STD*(R) values following an accelerometer bracket change. The other six cases were all associated with one particular output shaft. On inspection there is no evidence to suggest that the transmission was operating at a significantly different operating condition to that specified in Section 5. No record of any related maintenance action(s) could be found which could have caused the increase in vibration amplitude. One may therefore conclude that the amber warnings were triggered by vibration changes caused by normal operational variability. Why this particular shaft should be so sensitive is unclear. However only a slight amendment to the amber warning levels would eliminate the above exceedances.

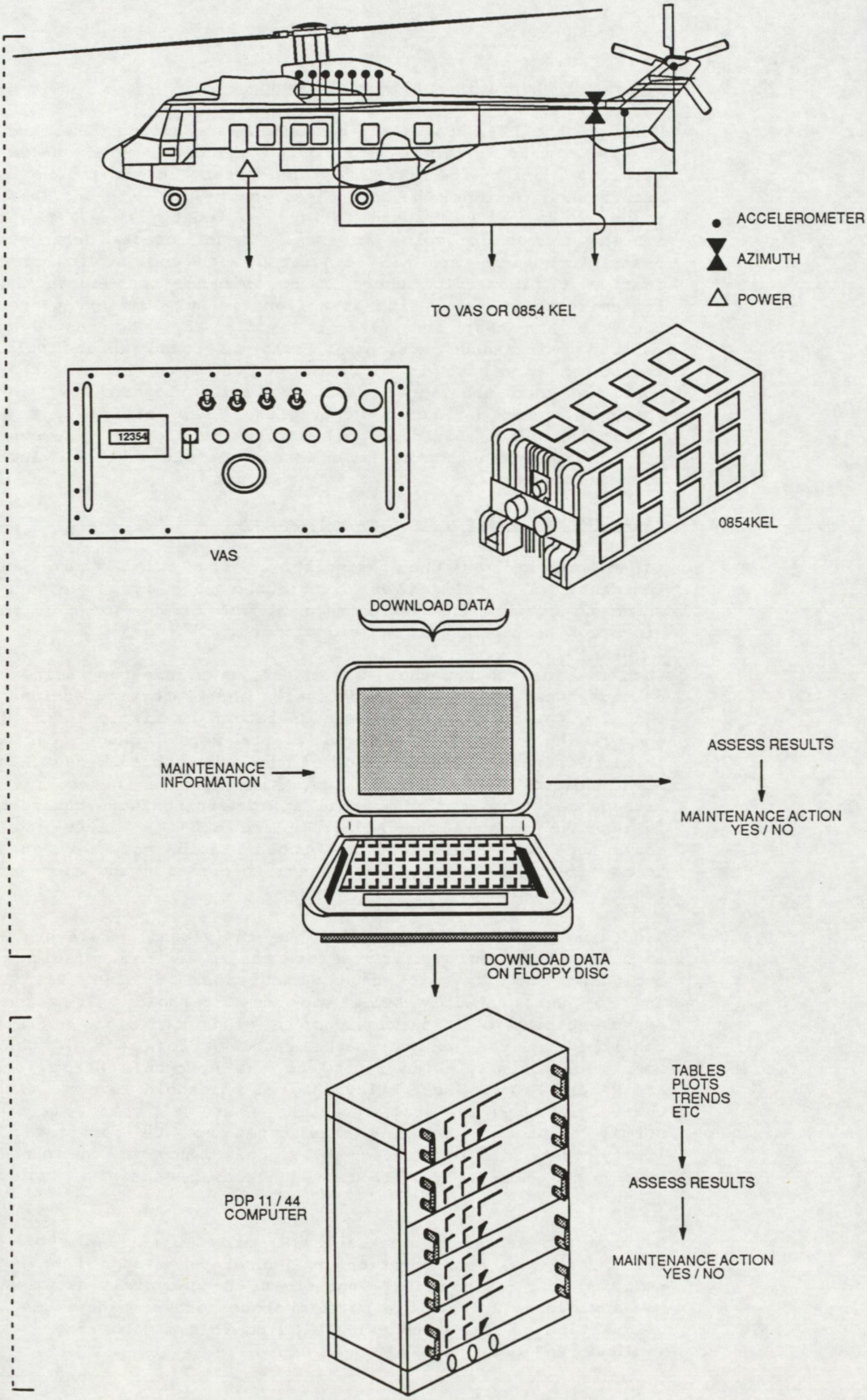
6.1.10. Fault Matrix and Its Primary Parameters

As anticipated at the beginning of the trial there were no incidents of localized or distributed gear tooth defects with which to confirm the performance of the fault matrix or the WHL vibration health monitoring algorithms.

When setting the threshold levels an inevitable compromise had to be made between early fault detection and protection against false flagging. With the red thresholds set at realistic levels it was encouraging that no false red alerts were produced during the trial. Only a slight revision of the amber thresholds would have been needed to eliminate the six genuine cases of amber exceedance. The four additional amber warnings were caused by the failure to redatum the PK-PK*(R) and STD*(R) values and these could have been avoided if the ground station computer had direct access to the necessary maintenance information and automatically redatumed the data.

Regarding the general range of the individual parameters, which make up the fault matrix, for the main transmission gears excluding the epicyclic stages, the values of PK-PK*(R), STD*(R) and M6* were sensibly below the red threshold values and were representative of transmissions in good condition. (This was confirmed by the strip reports received for some of the main rotor gearboxes). With regard to the epicyclic stages the PK-PK*(R) and STD*(R) were below the red threshold levels. However, there have been several occasions where M6* has exceeded the normal scatter. Although this could not be confirmed it is likely that this was caused by a deficiency in the processing system and not a true impulse generating mechanism within the gearbox.

Despite the values of the PK-PK*(R) and STD*(R) being below the red thresholds, consideration in future system should be given to reducing the fault matrix sensitivity to untypical datum values. One obvious solution would be to include more sample values in the calculation of the datum value. Using this method amber warnings would be reduced.



SCHEMATIC DIAGRAM OF DATA MANIPULATION AND INTERPRETATION PROCEDURES

FIGURE 9

6.1.10. Fault Matrix and Its Primary Parameters (Cont.)

Thus with regard to earlier trials, other rig test and aircraft failure experience and the general levels of variability seen in the results produced during this trial, it is WHL's opinion that if gear defects do occur in the Super Puma transmission they will cause the WHL vibration health monitoring parameters to respond with values adequately segregated from the normal scatter to cause a 'red' alert exceedance.

Therefore with strict control over redatuming of the parameter ratio's following any relevant maintenance actions and improvement to the processing system there is confidence that the WHL algorithms and parameters could successfully monitor the Super Puma transmission gears.

6.1.11. Reliability of Equipment

6.1.11.1. Reliability of Instrumentation

Even using a pre-production system there has been a low instrumentation failure rate (1 per 4378 airframe hours). Education to ensure that the installation is correctly reassembled after maintenance, and to prevent damage, allied with design modifications to protect from oil/water ingress and improve connector security might be expected improve the reliability by an order of magnitude. This gives confidence that a system could be installed and maintained by the operator during normal duties.

6.1.11.2. Detection of Instrumentation Faults

Improvements in the installation of the design will have a significant impact on the instrumentation reliability, but it is inevitable that faults will still occur. It is therefore important to be able to detect and rectify instrumentation faults at the earliest opportunity. During the trial WHL have investigated various methods of identifying these defects by way of an assessment of their effect on the vibration health monitoring parameters. For the majority of cases, a simple threshold level would have been adequate, but in some cases detection algorithms based on changes in the frequency spectra may be considered appropriate.

6.1.11.3. Reliability of VAS/0854 KEL System

After some delay in the initial trials installation the SI VAS/0854 KEL system performed reliably for the duration of the trial. Those system problems which did occur were of the type normally encountered in a demonstrator programme of this nature and SI provided technical assistance to BHL to resolve these. On occasions when the SI equipment was at fault the relevant units were repaired or replaced. As a result, a substantial amount of reliable data was gathered during the trials for subsequent analysis by the trials participants.

6.2. Oil Analysis

6.2.1. Oil Sampling (Off-Line)

In January 1988 a proposal for the use of additional techniques during the trial was accepted by the CAA. This was to "compare the performance of three different oil sample analysis techniques and correlate the results obtained with on-board gearbox health monitoring techniques".

The three techniques were:

a) Spectroscopic Oil Analysis Programme (SOAP)

Every oil sample received by Spectro Oil Analysis Company was analysed through the technique of low level spectrometric oil analysis capable of measuring the following significant elements at below one part per million (ppm):

a) Iron (Fe)
b) Chromium (Cr)
c) Aluminium (Al)
d) Copper (Cu)
e) Silver (Ag)
f) Nickel (Ni)
g) Titanium (Ti)
h) Silicon (Si)
i) Magnesium (Mg)
j) Tungsten (W)

b) Particle Quantifier (PQ)

This technique used a Particle Quantifier to provide a coarse indication of wear debris present in the oil samples, the direct measurement providing an empirical numeric value, the PQ Index. This value was included on the RPD analysis report sheet (Appendix B).

c) Rotary Particle Depositer (RPD)

This technique used a Rotary Particle Depositer to separate wear debris from the oil and to present it in a form convenient for microscopic examination by Swansea Tribology Centre (STC). The technique was thus a subjective technique without numeric values as a result. The report sheet (Appendix B) gave comprehensive analysis of particle types, plus a considered judgement of wear. It is claimed that this technique can be used to obtain detailed information about wear taking place on a less frequent schedule, and especially when any change takes place in the PQ Index or the SOAP concentrations.

6.2.1. **Oil Sampling** (Cont.)

The two laboratories contracted by the CAA to undertake the analysis were:

1. SPECTRO Ltd - SOAP

2. SWANSEA TRIBOLOGY CENTRE (STC) at the University College Swansea - PQ and RPD

Note:- Although not part of the CAA trial a third laboratory, CENTURY OILS Ltd, approached BHL in the early quarter of 1989 and made it known that they wished to join the oil analysis sampling programme and their services which included SOAP and PQ analysis were offered free of charge.

6.2.2. **Oil Sampling (Off-Line) Procedures**

Oil samples were taken from the specified Main Gearbox approximately every 50 flying hours.

Oil samples were taken within 20 minutes of shut-down.

The samples were posted, using containers, labels and stationary supplied, by the relevant laboratories.

Results were normally received, through the post, at the BHL Design Office, Redhill and at the HUM office in Aberdeen. Results which the laboratories considered required urgent attention were first telephoned though to the BHL Design Office, with the paperwork following as normal.

Any oil analysis data that required further action or investigation, was actioned by the staff in Aberdeen.

6.3. **Oil Debris Monitoring (On-Board)**

Electric chip detectors give a "GO"/"NO GO" indication without the ability to trend. Zapper chip detector distinguished fines (dust like wear particles) from chips but still remained a "GO"/"NO GO" indicator.

QDM MK1 has the ability to trend in two sizes of debris chip but there is the possibility that it may be swamped by fines and subsequently not detect chips that might occur as a result of a failure.

When it was decided back in 1987/88 to trial a full flow debris monitoring device it offered the following features:

- Capable of measuring varying sizes of debris.

- Count the number of chips/debris.

- Discriminate between ferrous and non-ferrous metal.

- Easily adjusted to cater for different alert levels.

6.3. Oil Debris Monitoring (On-Board) (Cont.)

It was originally intended to fit a TEDECO Lubriclone Quantative Debris Monitoring (QDM) sensor for the trial, but this form of installation was not acceptable to Aerospatiale (unacceptable pressure drop). So the QDM was therefore replaced by a "Ferroscan" system supplied by Sensys of Canada was fitted during the trial. Sensys supplied one complete system for the first fully installed helicopter health monitoring trial (G-TIGE).

6.3.1. Theory of Operation "Ferroscan"

A typical Ferroscan sensor consists of a length of pipe surrounded by an annular electromagnet assembly. This assembly contains another magnetizing coil, and an inner detector coil.

The magnetising coil traps ferrous debris within the inner detector coil causing a change in the inductance of the latter. This change in inductance is detected by a change in the resonant frequency of the RF circuit to which the detector coil is connected. The concentration of ferrous material in the oil is proportional to the rate of change of the resonant frequency. By applying different values of the current in the magnetising coil an assessment can be made of the mean particle size.

6.3.2. Ferroscan Trial

The system consisted of a full flow 1 inch internal diameter sensor welded into the main gearbox oil scavenge pipe and a micro controller mounted inside the HUMS cabinet. This sensor was only capable of monitoring ferrous debris, (eg. iron, steel, nickel alloys), but was shown to detect particles as small as a few microns in diameter.

When the Ferroscan system arrived in November 1988, it was taken to WHL for testing using their oil test rig. The tests provided valuable information, which indicated that the package appeared to offer an acceptable system. The sensor was then despatched to Aberdeen, where it was found that the sensor fouled the return pipeline from the oil cooler and the sensor had to be returned to Sensys for rework.

The complete system was finally cleared for installation in late April 1989.

6.3.3. Ferroscan Potential

The system offers the potential to detect and quantify both ferrous and non-ferrous debris in a mobile fluid lubrication system. It would appear to work adequately in a basic test rig configuration. But future tests must include EMC testing, air/fluid mixture, vibration, temperature cycling, varying power supplies and optimum bore size. The system at the end of the trial failed by a large margin to meet an acceptable airworthiness standard of equipment performance and the complete system has been returned to Sensys.

6.4. Rotor Track and Balance (RTB)

The BHL proposal to the CAA identified that the methods used in 1987 (and still in use today) for detecting rotor mass imbalance, blade tracking and general airframe vibration irregularities did not accurately reflect the helicopter operational conditions. For example, the AS332L helicopter AUW at the start of a typical revenue flight may be in excess of 18000 lbs, whereas the RTB work may have been carried out at an AUW of 16000 lbs. Furthermore, many of the techniques relied on the ability of the line engineer to interpret vibration and blade positional measurements, which resulted in loss of consistency. MJA Dynamics was contracted by BHL to develop an RTB software package for the AS332L helicopter as a part of the trial based on their previous military experience.

First track and balance sensors were installed in a helicopter, in order to collect data under conditions experienced in operational service. A Stewart Hughes (SHL) passive tracker sensor fitted in the nose of the helicopter, (ref. Figure 4), was connected to an SHL RADS interface unit located in the health monitoring cabinet, which supplied tracker data to the SI airborne computer (0854 KEL). This data combined with airframe vibration data was stored in non-volatile memory, ready for downloading for ground based analysis via the DTU. About 5 months was spent by SI, SHL, MJAD and BHL resolving various interface problems that arose, but once this was achieved, the hardware proved to be very reliable.

Second, in parallel with this activity, data collection hardware (SHL RADS) was used to collect blade positional (tracker) and airframe vibration measurements on non-revenue flights, where dedicated test flying and main rotor adjustments could be undertaken. This work was necessary to elicit adjustment sensitivities, and develop the software which would eventually support the analysis of data downloaded from the SI airborne computer. Adjustment sensitivities, which define the relationships between RTB measurements and a unit adjustment, were established for blade spanwise mass, blade tab and blade pitch link adjustments. The SHL RADS was also used to check the airborne system once all the interface difficulties had been addressed.

The software driven diagnostic strategy was based upon operating on all of the tracker and airframe vibration data simultaneously. The latter was reduced to the component in the vibration data which has a frequency identical to the main rotor turning frequency, namely 1R. To improve the signal to noise ratio in the measurement sets, data averaging was used throughout. This part of the trial imposed a heavy burden on the BHL (Aberdeen) team, not only the engineers, but also the pilots. To gather the data in flight the pilot was required to initiate the collection process at six (6) different steady states and one transient condition (see Appendix A).

6.5. Airframe Vibration

The previous section referred to the 1R vibration component. The airframe vibration signature is composed of a number of harmonics, one of which is associated with the blade pass frequency, bR, where b is the number of blades. Numerous airframe related faults can give rise to excessive bR vibration levels.

For the trial there were 3 accelerometers fitted, one under the co-pilot's seat and two in the avionics cabinet. The accelerometers were connected to the BHL interface box, which in turn passed the data to the airborne computer to be held in non-volatile memory.

6.6. Monitoring of Control Loads and Critical Temperatures

In order to monitor in-flight loads (i.e. any flight pattern or all up weight that might cause the strain gauge data to change) and heat build up (usually indicative of wear, lack of lubrication or failure) in components, during daily operational flights, it was decided to install strain gauge and thermocouple sensors.

6.6.1. Strain Gauging

BHL discussed with various parties including Welwyn Strain Management (WSM) their recommended locations for the attachment of strain gauges. BHL installed eight (8) strain gauges at the following locations:

1 Strain Gauge to each servo on the MGB (3 off)
1 Strain Gauge to each MGB support strut (3 off)
1 Strain Gauge at FRAME 9000
1 Strain Gauge at TGB SERVO LINKAGE

The signals from the strain gauges were fed into the BHL interface box and buffered and amplified before being passed to the SI 0854 KEL computer. The signals were recorded in non-volatile memory for downloading to the DTU and for possible display on the CDU.

6.6.2. Bearing Temperature Monitoring

Tail rotor driveshaft support bearings have on occasion in the past failed in service, it was therefore decided to see if there existed any relationship between temperature and bearing failure but alas there were no bearing distress arisings during the trial.

Six thermocouples, one to each of the tail rotor drive shaft bearing housing. Signals from the thermocouples were passed to the BHL interface box and from there to the SI 0854 KEL computer. The data was then down loaded via the DTU and transferred to a stand alone PC. It was also possible to view the data on the CDU.

6.6.2. <u>Bearing Temperature Monitoring</u> (Cont.)

The temperature bands were first set by SI on figures provided by BHL after temperature tests were carried out during engaged rotors ground runs. Table 1 below details the temperature bands as it was initially defined and Table 2 details the temperature bands adjusted by BHL to reflect a more accurate picture of bearing temperature behaviour as seen during the data gathering in 1989.

TABLE 1 (SEE FIG. 10)

BAND 1	< 40°
BAND 2	40 - 50°C
BAND 3	50 - 60°C
BAND 4	60 - 70°C
BAND 5	70 - 80°C
BAND 6	80 - 90°C
BAND 7	90 - 100°C
BAND 8	100 - 105°C
BAND 2	105 - 110°C
BAND 10	110 - 115°C
BAND 11	115 - 120°C
BAND 12	120 - 125°C
BAND 13	125 - 130°C
BAND 14	130 - 135°C
BAND 15	135 - 140°C
BAND 16	>140°C

TABLE 2 (SEE FIG. 10A)

BAND 1	Less than 13°C
BAND 2	13 - 17°C
BAND 3	18 - 20°C
BAND 4	21 - 23°C
BAND 5	24 - 27°C
BAND 6	28 - 30°C
BAND 7	31 - 33°C
BAND 8	34 - 35°C
BAND 9	36 - 37°C
BAND 10	38 - 39°C
BAND 11	40 - 41°C
BAND 13	42 - 43°C
BAND 13	44 - 45°C
BAND 14	46 - 47°C
BAND 15	48 - 49°C
BAND 16	50°C and above

The bearings predominantly operate in bands 1 to 7 of Table 2.

THERMOCOUPLES HISTOGRAM (Table 1)

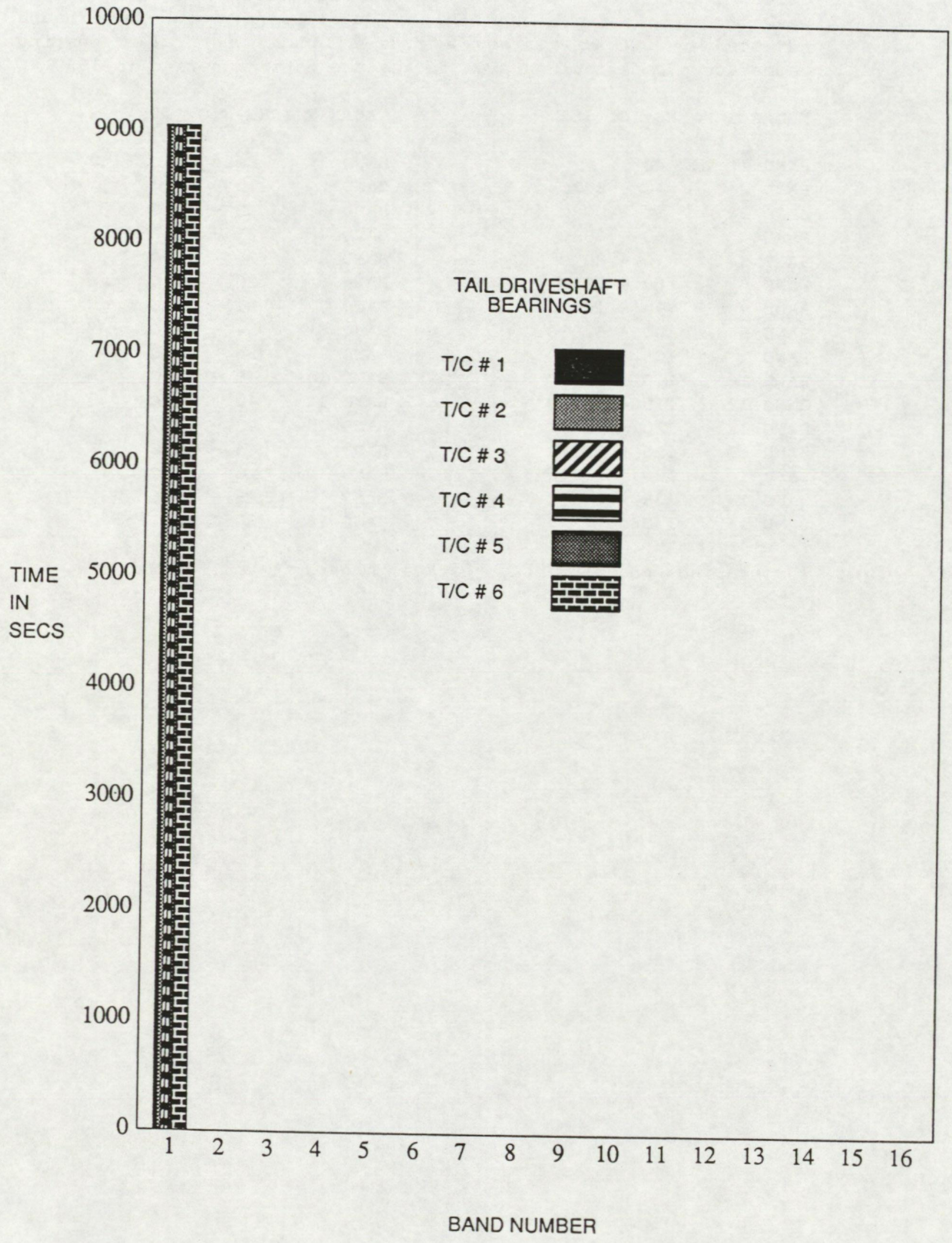


FIGURE 10

THERMOCOUPLE HISTOGRAM (Table 2)

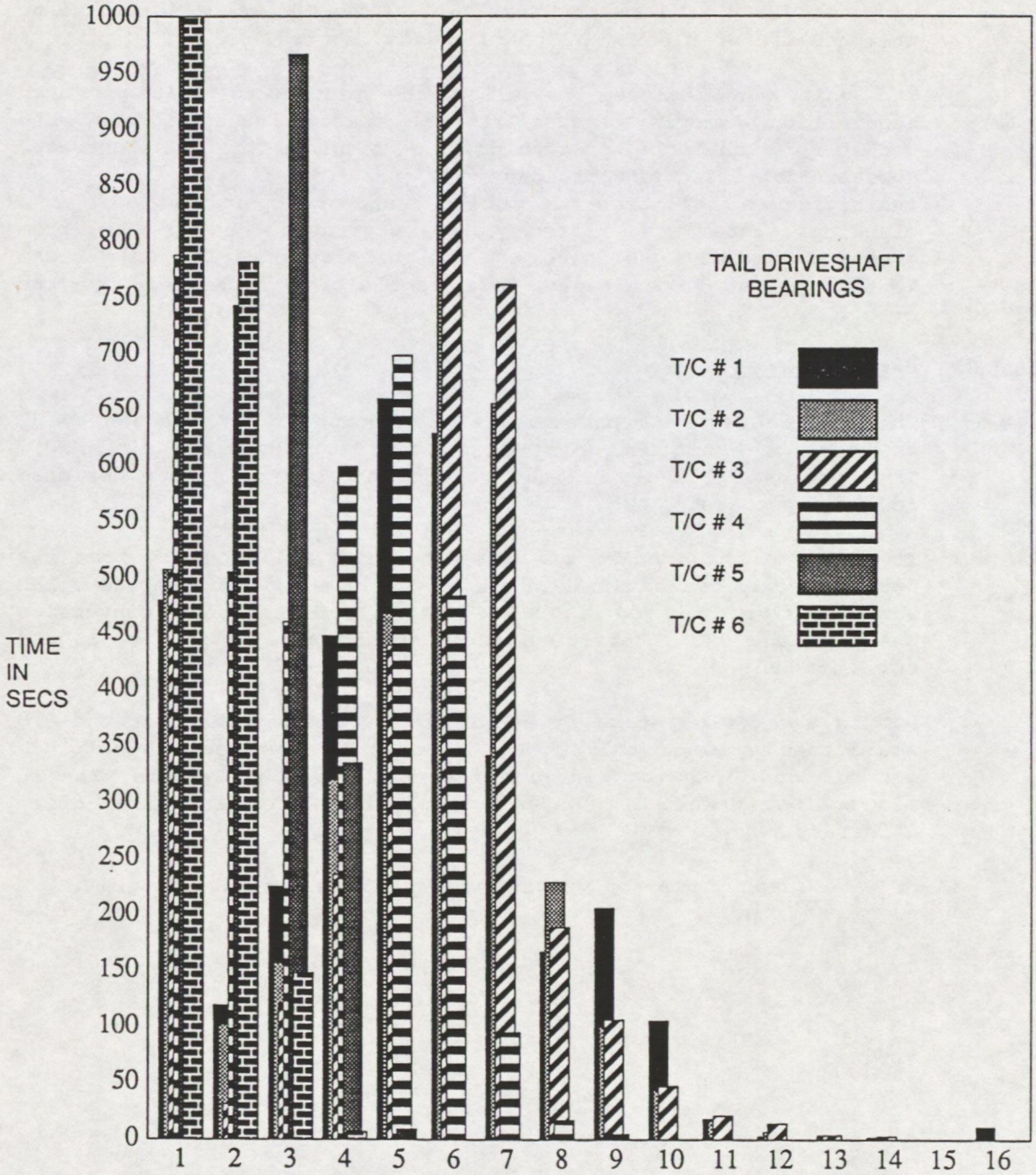


FIGURE 10A

6.7. Control Display Unit (CDU)

The CDU consisted of a small colour CRT display with ten numeric keys and 23 other function keys. The unit was mounted on the centre console in the cockpit and connected to the airborne computer (0854 KEL) by an RS422 link. The CDU was also linked to the Data Transfer Unit (DTU), reference Figure 11.

The unit was designed to allow the pilots to initiate data acquisition, display system status, sensor input signals, and results of on-board processing, as required by the Contract. However following discussions with the CAA it was decided to inhibit some facilities for public transport operations and so a blanking plate was fitted which prevented the pilots from pressing the keys relating to data display, leaving only those keys required to initiate data acquisition accessible to the pilot.

6.8. Data Transfer System

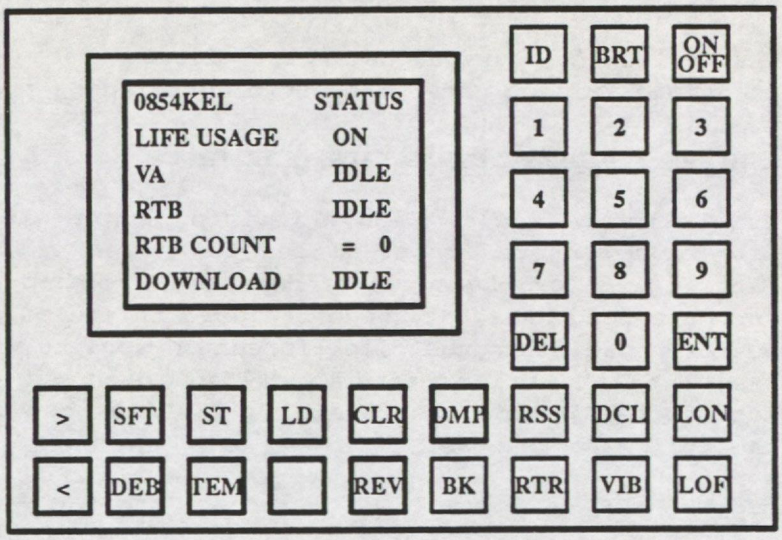
The Toshiba T1000 (a portable lap-top computer) was chosen by SI as being the most suitable PC for the Data Transfer Unit (DTU). The Toshiba T1000 is a light weight portable computer, designed for word processing.

To overcome the problem of switching from RS422 output from the 0854 KEL computer to RS232 protocol for the lap top computer, BHL were required to add an RS232/RS422 bi-directional conversion board to the BHL interface box (the board was designed by SI and built by BHL).

During the design stage of the trial it was thought that the DTU would take approximately 2 to 4 minutes to download one complete set of data. However in practice this was usually more than 15 minutes per download. Refer to Appendix C for a typical daily itinerary.

SI were responsible for writing the download software program.

CONTROL DISPLAY UNIT (CDU)



KEYBOARD FUNCTIONS

ID	:–	System Identification
BRT	:–	Brighten / Dim Display
ON / OFF	:–	Not applicable to this installation
0 – 9	:–	Numeric Key Pad
DEL	:–	Delete
ENT	:–	Enter
>	:–	Page Increment
SFT	:–	Shaft (M6* Values etc. Not applicable for this trial)
ST	:–	Status
LD	:–	Loads / Strains Gauge (Not applicable for this trial)
CLR	:–	Life Usage Clear (Press Twice)
DMP	:–	Dump (Down Load Data)
RSS	:–	Rotor Track and Airframe Vibration (6 States)
DCL	:–	Dynamic Control Loads (Individual loads not applicable for this trial)
LON	:–	Life Usage ON
<:	:–	Page Decrement
DEB	:–	Debris Monitor (Not applicable to this installation)
TEM	:–	Temperature (Tail Drive Shaft Bearings)
DVM	:–	Digital Voltmeter (Not applicable to this installation)
REV	:–	Revolutions(Normally set to 40 but may be adjusted for specific tests)
BK	:–	Break (Aborts any process)
RTR	:–	Transient Rotor Track and Balance
VIB	:–	Gearbox Vibration
LOF	:–	Life Usage Off

FIGURE 11

7.0 SUMMARY OF TRIALS RESULTS

On average the helicopters flew twice daily, but due to the limitations of the equipment never more than one download of data was achieved daily per helicopter.

The following paragraphs will address each health monitoring technique trialed under the title detailed on previous pages.

7.1 Gearbox Vibration Monitoring Results

The helicopters flew 12649:25 flying hours with all the gearbox vibration sensors installed and 536 files of data were gathered (see Fig. 8 for breakdown of database). About 80 files contained corrupted/bad data, of these 54 were attributed to pilots (in over 50% of these files the pilot forgot to acquire, the remainder were caused by the pilots heavy workload which did not allow time to acquire data) and the remaining 26 files contained bad data for the following reasons:

Type of defect		No. of accelerometer defects
a)	Loose or disconnected micro-dot connectors	19
b)	Contaminated (oil and moisture ingress) micro-dot connectors	4
c)	Other defects	3

The breakdown of the 26 corrupted files against the gearboxes is as follows:

Main Gearbox	18 corrupted files
Intermediate Gearbox	7 corrupted files
Tail Gearbox	1 corrupted file

The remaining 456 files were analysed using the WHL algorithm and produced generally consistent results in the form of Health Monitoring parameters.

The gearbox mounted accelerometers (45 at the peak of the trial) accumulated more than 100,000 flying hours in service without a single failure.

Primary assessment of gearbox condition was carried out at Aberdeen by comparing the health monitoring parameters stored in the downloaded data against a WHL developed fault matrix. The matrix then gave one of three states for each shaft/gear, green for normal, amber for cautionary and red for damage or defect.

During the trial no red alerts were triggered and consequently no gearboxes were rejected by vibration health monitoring. Ten amber warnings were triggered but these were caused by faulty connectors, wiring or failure to redatum the matrix after a maintenance action.

7.1 Gearbox Vibration Monitoring Results (Cont.)

Data collected during the trial at various stages were as follows:

Stage	No. of Download (FILES)
TEAC DATA	71 - 6526.40 A/F Hours
VAS DATA	182 - 4359.00 A/F Hours
0854 KEL DATA	283 - 2091.00 A/F Hours

7.2. Oil Sampling Results (Off-Line)

During the trial BHL despatched 344 oil samples to the three laboratories for them to conduct their oil analysis techniques. They all performed their analyses within 48 hours of receipt of the samples and transmitted their results to BHL.

No defects were highlighted by any of the three oil analysis techniques (SOAP, PQ and RPD), but on two occasions it was possible to track back after a bearing failure and see some evidence of bearing spalling 50 to 80 hours before the failure was detected by the chip detector, but in this instance not conclusive enough to base any diagnostics theory on.

The RPD analysis was a subjective technique without numeric values (refer to Appendix B), which did not easily lend itself for inclusion in computer based trending analysis. It is believed that these limitations can be overcome by supplementing numerical values for technical description of debris in oil.

7.3. Oil Debris Monitoring Results (On-Board)

The Sensys "Ferroscan" debris monitoring system was installed for 722 flying hours during which time a total of 67 files of data were downloaded. Upon examination, the data obtained in flight was found to be unreliable to the point of being of little or no value.

The systems generated RF emissions, which affected the helicopter's VHF radio reception, and corrupt data which was believed to have been caused by temperature variation, vibration and power supply problems.

7.4. Rotor Track and Balance Results

Over 280 files of RTB data were collected during the trial. The majority of these files were used to troubleshoot problems with the various hardwares and their respective interfaces. Further validation exercises were also undertaken, where the airborne system output was benchmarked against the SHL RADS system.

7.4. Rotor Track and Balance Results (Cont.)

Analysis of the SHL tracker data established that only 60% was usable. Loss of measurement accuracy arose when the tracker was pointing directly into sunlight or sufficient contrast was not realised between blade and background. To alleviate this shortcoming both raw and refined analyses were developed by MJA Dynamics Limited (MJAD). In raw analysis, only the airframe vibration information is used to determine the state of the rotor. Refined analysis uses both vibration and tracker information, in order to determine adjustment recommendations. Refined analysis is more complete in that it will not only reduce the 1R airframe vibration but will, where possible, mitigate any rotor positional asymmetry. Raw analysis minimises 1R airframe vibration only.

Analysis of the airframe vibration signatures indicated that the 1R component was being swamped by higher frequency components, which resulted in loss of 1R measurement accuracy. This situation was rectified by a hardware modification, which filtered out the higher frequency components prior to analogue to digital conversion. Unfortunately, this limited the usefulness of the data when considering general airframe vibration irregularities (see section 8.5).

It was found that if data was actually collected at the prescribed test points and an experienced line engineer was called upon to carry out the recommended adjustments, successful main rotor maintenance was realised. This was established for three adjustment categories, namely mass, tab and pitch link, and combinations thereof. The maximum number of successful maintenance actions recommended by the MJAD software package, based on data from one flight, was six (6). This exceeded the capability of even the most experienced line engineer. Over the trials period, however, measurement quality did vary to the extent that data integrity checks had to be undertaken, prior to carrying out adjustment diagnostics. Problem sources included measurement error, incorrectly fitted sensors, loose accelerometers, blade identification misunderstandings and incorrectly carried out maintenance actions.

Whilst reducing the induced airframe vibration is a desirable objective, the vibration itself may be symptomatic of a non-adjustable fault. Caution therefore has to be exercised in ensuring that such symptoms are not suppressed by main rotor adjustments. One such class of fault encountered on the trial was a mis-match in the main rotor frequency adaptors (lag dampers). Measurement patterns in the 1R vibration and blade positional measurements were established for the case encountered which identified the problem. It is feasible that such a pattern could be searched for in every HUMS downloaded data set and reported on the HUMS groundstation computer.

7.4. Rotor Track and Balance Results (Cont.)

It is possible that certain classes of non-adjustable fault, if left undetected, could give rise to catastrophic failure. Such potentially catastrophic faults (PCFs) need to be detected as early as possible if a meaningful safety benefit is to be realised. During the trial other forms of data capture not required for RTB adjustment work were investigated. One area which holds some promise is the acquisition of non-averaged, rev by rev, blade positional information. Such blocks of data may span a time period equivalent to 128 main rotor revolutions. Pattern changes in these data sets could trigger a cautionary warning on the HUMS groundstation computer. However, the data did require a high degree of expert interpretation and further work needs to be undertaken to simplify the analysis before it could be applied by the line engineer.

The trial has established that RTB adjustment diagnostics may be successfully performed by a software based system given good quality data and an experienced line engineer. Further effort needs to be expended however on understanding the symptomatic behaviour of both non-adjustable faults and PCFs, in order that a meaningful safety benefit may be realised.

7.5. Airframe Vibration Results

Due to the hardware modification to the airborne system cited in the previous section, the acquired airframe vibration was limited to 1R. However, based on the acquired accelerometer signatures, a number of general observations are made in para 8.5.

7.6. Monitoring of Control Loads and Critical Temperatures

7.6.1. Strain Gauges

Strain gauge data was tabulated as histograms showing the time spent in sixteen strain bands for each gauge, and on every flight a snapshot of data from a selected gauge was recorded to provide information about the strain fluctuations present. Having examined the data, BHL established that the data had the expected general characteristics. However, as Aerospatiale did not define the normal strain levels of the instrumented component, no conclusions could be drawn from this data without further constructor investigation/analysis.

The frequencies seen in the snapshot records are of interest but tend to be mostly 1R or 4R in origin and this is not really surprising bearing in mind that this is the major source of vibration on the aircraft.

This part of the trial clearly demonstrated that it is imperative to seek and obtain the active involvement of the manufacturer, because without their help, the data obtained could not be assessed by BHL.

7.6.2. Bearing Temperature Monitoring

None of the bearings being monitored suffered a failure and as there was no previous established alert levels, the data collected could not be assessed satisfactorily.

Once again it has been demonstrated that reliable and consistent data can be collected, but a lot more bearing failure test work needs to be carried out before any definite conclusions could be drawn and criteria laid down by the constructor for the inspection/removal of bearings.

7.7. Control Display System Results

The CDU proved to be a reliable unit, that worked for over 2,000 flying hours and only suffered one minor defect (power supply problem) which was repaired by S.I. within 24 hours.

7.8. Data Transfer System Results

To achieve the 283 downloads during Stage III of the trial, more than 500 attempts were made to download the data. Some of the reasons for unsuccessful first attempts were:-

a) 3½" diskette was not correctly formatted
b) 3½" diskette faulty (i.e. scratched)
c) Failure of Toshiba internal power supply
d) RS232 cable problems
e) Incorrect use of keyboard
f) Aircraft power supply failure

The Toshiba only failed once during trial when one of the components (micro chip) was found to be defective.

8.0. CONCLUSIONS

This trial has clearly demonstrated that various health monitoring techniques could be designed, installed and operated in helicopters engaged in everyday flying operations over the North Sea.

From an assessment of the results of the trial the following conclusions can be drawn:

8.1. Gearbox Vibration Monitoring

a) High quality reliable data was obtained during the trial and served to identify areas for further refinement, eg. improved vibration signature acquisition with a better signal to noise ratio, better discrimination and processing using floating point arithmetic. The trials indicated a consistency in the results and a sensitivity which gave some confidence in the ability of the bench proven diagnostics to identify defects arising in flight.

b) Automatic acquisition of data is essential, to ensure that the data is collected on every flight during the same flight conditions. The pilot should only have to acquire data if he has experienced any abnormal conditions.

The performance of the WHL algorithms and the fault matrix shows that there should be no restriction to their application to monitor the Super Puma transmission on a routine basis.

The trial has clearly demonstrated that, subject to the recommendations discussed in this report being incorporated, a gearbox vibration health monitoring system could be designed, installed and operated to successfully monitor the Super Puma. The trial has also demonstrated that the Westland gearbox diagnostics can be adapted to other helicopter types.

c) The reliability of micro dot connectors must be improved.

d) The system must be capable of carrying out its own self test and alerting the maintenance staff of any problems. This would eliminate many hours spent identifying the cause of spurious warnings.

e) The reliability of the instrumentation has been such that one could envisage that a system could be installed, used and maintained during normal revenue flying.

8.2. **Oil Sampling (Off-Line)**

a) Off-line oil sampling is a very labour intensive system with the cost per sample working out at approximately £65 for the trial.

b) Off-line oil analysis is a very important indication of wear or damage, but its role in the future may be determined by the success or failure of on-board oil debrisv monitoring systems.

c) Manufacturers must provide suitable ports for extracting oil samples.

d) Oil sampling (off-line) is an excellent secondary check to confirm or reject a suspected problem.

8.3. **Oil Debris Monitoring (On-Board)**

a) The Ferroscan system was not found to be suitable for trials on a helicopter and should be further developed until the problems identified have been resolved.

b) There is a definite need for an on-board oil debris monitoring system. BHL believe that the Ferroscan system, as trialed, is at least two years away from being certificated.

c) The Ferroscan is restricted to detecting ferrous particles only and any on-board system that is eventually fitted should be capable of detecting both ferrous and non-ferrous particles. Sensys did think that it was an achievable goal.

8.4. **Rotor Track and Balance**

a) The trials established that the software based 1R vibration and blade positional diagnostic package supplied by MJA Dynamics Limited could identify main rotor irregularities covering spanwise mass, blade tab and pitch link adjustments. It was important however that the package was supplied with accurate data and any recommended actions were carried out by an experienced line engineer. The maximum number of successful maintenance actions, based on measurements from one flight, was six. This exceeded the capability of even the most experienced line engineer.

b) Equally as important as the adjustments diagnostics is the requirement to carry out robust data integrity checks. Problem areas encountered in the trial include measurement error, incorrectly fitted sensors, loose accelerometers, blade identification misunderstandings and incorrectly carried out maintenance actions.

8.4. **Rotor Track and Balance** (Cont.)

c) In addition to main rotor maladjustments, non-adjustable faults must be considered in the diagnostic process since these faults can give rise to similar measurement symptoms as adjustment faults, affecting both 1R vibration and blade vertical (track) and inplane (lag) positions. One such class of fault is mis-matched frequency adaptors (lag dampers). For the one case of adaptor mis-match encountered on the trial, measurement patterns were established which identified the problem.

d) Beside data averaging techniques, which are used throughout the adjustment diagnostics, other forms of non-averaging analyses were also investigated. The objective here was to see if additional diagnostic information could be extracted from larger data blocks. Such information may offer the opportunity to detect potentially catastrophic faults (PCFs- eg. composite blade fracture, blade leading edge separation and lag damper detachments) early enough to give a meaningful safety benefit. One area which holds some promise is the acquisition of blade positional data over a number of main rotor revolutions. By avoiding data averaging, temporal changes in individual blade positions could be monitored and measurable irregularities reported. However, the data did require a high degree of expert interpretation and further work needs to be undertaken to simplify the analysis before it could be used by the line engineer.

8.5. **Airframe Vibration**

During the trial the airborne acquisition system was modified to ensure good resolution of the vibration measurements required for main rotor adjustment diagnostics. Unfortunately this precluded the possibility to monitor airframe vibration frequencies greater than 1R (fundamental main rotor turning frequency). However, based on the accelerometer signatures acquired a number of general observations may be drawn:

a) Mechanical faults have a varying affect on vibration throughout the airframe. Accordingly, to offer adequate visibility of a range of faults, it will be necessary to distribute accelerometers throughout the airframe.

b) The facility to capture blocks of non-averaged data should be extended to cover vibration acquisitions. By avoiding data averaging it may be possible to elicit features from the accelerometer signatures which would otherwise be masked by the averaging process.

c) It will be necessary to establish criteria by which the contribution of the "mechanical condition" to the measured airframe vibration levels is separated from the contributions made by the helicopter operational state and ambient conditions. This will be necessary to reduce false alarms.

8.6. Monitoring of Control Loads and Critical Temperatures

8.6.1. Strain Gauges

The attachment of strain gauge sensors required specially trained engineers and involved a lot of extra work. However, once installed the gauges were found to be reliable but the results could only have been of value if the manufacturer had been fully involved from the start.

This type of monitoring system is not suitable for retrospective embodiment but could be considered by helicopter manufacturers for embodiment into new helicopter types.

8.6.2. Bearing Temperature

The trial proved that reliable data could be collected by attaching sensors to the outer housing (casing) of each bearing, but as there were no distress of bearings, it is not possible to identify any predetermined alert levels. The constructor needs to establish these.

8.7. Control Display System

The CDU met the requirements of the design phase of the trial but was found to be unsuitable for a permanent installation because:

a) A high level of pilot concentration was required
b) The readability of the display was poor
c) Software lacked flexibility

It is highly desirable in any future Health Moniroting Systems to display exceedance and to enable flight crew to enter data, the problems highlighted above must be resolved.

In addition the Cockpit Display Unit should be menu driven with no pilot inputs required for normal acquisition of data.

8.8. Data Transfer System

The use of a portable computer to transfer data from only two aircraft was acceptable for a limited period of time, but this method could not be sensibly adopted on any future fleetwide health monitoring system for the following reasons:

a) Trial download time ranging from 25 minutes to 120 minutes is not acceptable. Three to five minutes should be the maximum timescale for a download. An excessive amount of engineers time spent trying to download data.

b) Faulty diskettes.

c) Toshiba internal battery (1 hour duration) could not cope with protracted downloads.

To be acceptable in a real operational world the DTU needs to be fast, reliable and easy to use, i.e. data should be recorded onto a transferable medium, eg. tape or disk.

9.0. SUMMARY

This trial has led to a better understanding of helicopter Health Monitoring Techniques systems and procedures, making it possible to seriously consider the retrospective installation of a health monitoring package to improve the safety, health and maintenance management of helicopters.

The trial has demonstrated that certain techniques are suitable for use in the normal helicopter operating environment, whilst others require further development as detailed below:

a) The installation and instrumentation has been shown to be reliable in service providing care is taken during maintenance activities.

b) The basic Westland diagnostic suite was readily adapted to the requirements of the AS332L Super Puma and produced consistent results during the trials demonstrating that the diagnostics could be similarly adapted for other conventional helicopter types.

c) MJA Dynamics diagnostics for the on-board rotor track and balance were successfully adapted for the AS332L Super Puma demonstrating their ability to deal with rotor track and balance problems in other articulated helicopter rotor systems.

d) The multi R vibration response of the helicopter is already known to be conditioned by a number of airframe defects. The diagnostic capability of multi R vibration signature response has been progressed but does require a larger data base of known defects with particular response characteristics to enable this powerful maintenance and safety tool to be developed.

e) Off-line oil sampling analysis on a regular basis was found to be unsuitable on the grounds of manpower and cost per sample, but is worth considering as a complementary technique to confirm a defect.

f) Advanced on-board oil debris monitoring systems will form an essential part of any future health monitoring system. This is one area where progress is required to develop practical systems.

g) The development of strain gauge and bearing temperature data diagnostics is best left to the manufacturers.

h) Automatic acquisition of data has been shown to be an essential part of any future Health and Usage Monitoring System.

i) Simple and unambiguous pilot interface with the system is required.

9.0. **SUMMARY** (Cont.)

j) For the purposes of the trial the gearbox vibration analysis was conducted in the airborne computer but as a result of the difficulties experienced during the trial and taking into consideration the need to be able to change the values of any transmission vibration diagnostics algorithm, careful consideration should be given to future designs as to whether at this stage in the development of health and usage monitoring transmission diagnostics should be conducted on-board, particularly if it is not feasible or desirable to display the processed information during flight.

k) The development of Health and Usage Monitoring Systems should be continued around a Ground Based Diagnostics System until the maturity of the techniques and systems are established from a fleet data base. It makes financial and good management sense to restrict the initial updating of software to a ground based system as opposed to an on-board processor, especially when one considers the different types of helicopters that have to be accommodated by the system.

l) The manhours required to maintain and operate a HUM system within an operators fleet obviously cannot be established from the trials programme. However during late 1991 and 1992 an increasing number of aircraft will be operating with HUM systems which will begin to reveal the true maintenance manhours involved with the support of this type of system. This can then be compared with the commensurate offset of improved diagnostics extension to maintenance schedules and component T.B.O.s

10.0. ACKNOWLEDGEMENTS

Bristow Helicopters Limited with to take this opportunity to thank all the participants for their co-operation and support during the last three years that this trial has spanned, i.e. 1987 to 1990.

APPENDIX A

HUM DATA ACQUISITION PROFORMA

HUM DATA ACQUISITION PROFORMA FOR:– G –

GENERAL

1. During your flight, you are requested to assist in the acquisition of data which will make a valuable contribution to the development of a comprehensive Health and Usage Monitoring (HUM) system for helicopters.

2. The actions required are simple key presses at specified conditions to initiate the acquisition process. The sequence of key presses, and the screen displays which should appear, are shown on the following proformae.

3. The equipment SHOULD power–up when the TRU's are 'on–line'. If the screen remains blank then press the ON–OFF key. Some keys are guarded and no attempt to press them should be made.

4. The BRK key may be used to abort a process before its completion.

5. The DMP key is for the use of ground engineers during data downloading.

6. The DEL key may be used to delete an entry from the keypad.

7. It should be remembered that a STATUS page will appear on the screen if no key presses are made for a period of 15 seconds. A typical STATUS page is shown here:

8. ON NO ACCOUNT SHOULD THESE HUM TESTS BE ALLOWED TO INTERFERE WITH THE SAFE OPERATION OF THE AIRCRAFT.

0854KEL	STATUS
LIFE USAGE	ON
VA	IDLE
RTB	IDLE
RTB COUNT	= 0
DOWNLOAD	IDLE

THE TESTS

9. The tests in flight may be carried out IN ANY ORDER. You are advised to look through the following proformae before the flight so that you are aware of the requirements.

10. The tests fall into four categories:

    a. Rotor track and balance – steady state (RSS) (in daylight only)

    b. Rotor track – transient (RTR) (in daylight)

    c. Dynamic control loads (DCL)

    d. Gearbox vibration (VIB)

11. For more details on the equipment, see Flying Staff Instruction UH89/002.

IMPORTANT NOTE

IT IS ESSENTIAL TO PRESS THE LOF KEY BEFORE THE ALTERNATORS ARE TAKEN 'OFF LINE' AT THE END OF THE FLIGHT.
IMPORTANT DATA WILL BE LOST UNLESS THIS PROCEDURE IS USED.

AFTER FLIGHT

PILOT: Please leave this form with the Tech. Log

LINE OFFICE: Please return this form to the HUM engineer.

HEALTH AND USAGE MONITORING SYSTEM – INITIALIZATION ISSUE No: 5

Record crew names CAPTAIN [ ] 2nd PILOT [ ]

ACTIONS REQUIRED AFTER SWITCHING ON THE BATTERY:

ACTION	KEY PRESS REQUIRED	SCREEN DISPLAY
1. If necessary, adjust screen brightness:	BRT	BRIGHT / DIMMING TEST SCREEN
	Alternatively press and hold to DIM or BRIGHTEN BRT	
2. Select title (IDENT) page display: Record date displayed: DATE [ ] Record time displayed (HH : MM : only) TIME [ ]	ID	SMITHS INDUSTRIES PLC 0854KEL V00. 14 (C) SIADS : 1988 DD / MM / YY HH : MM : SS READY
3. Set number of revolutions required for track and balance data:	REV	ENTER REV COUNT FOR USE IN RTB STEADY – STATE ANALYSIS (20 – 160) >>>
	[ ] [ ] [ ] ENT	STEADY – STATE RTB ANALYSIS NEW REV – COUNT ACCEPTED READY
4. Clear the life usage store:	CLR CLR (Double press required)	LIFE USAGE PARAMETERS HAVE BEEN RESET READY
5. Select life usage ON	LON	LIFE USAGE ANALYSIS NOW ENABLED READY

Enter take–off conditions AUW [ ] OAT [ ] PRESSURE ALTITUDE [ ]

ACTIONS REQUIRED TO EXECUTE DATA ACQUISITION – Carry out the following tests in any convenient order:

ACTION	KEY PRESS REQUIRED	SCREEN DISPLAY	TICK WHEN COMPLETED
1. ON THE GROUND (Daylight conditions only)			
ROTOR TRACK & BALANCE – STEADY STATE (RSS)			
TRIAL ID 1. With the collective fully down and both engines running with the SSL's in the FLIGHT position, initiate the data analysis:	RSS	RTB STEADY STATE ANALYSIS IN PROGRESS READY	
After approximately 30 seconds this screen will appear:		STEADY STATE RTB ANALYSIS COMPLETE ENTER TRIAL ID (1 – 6) >>>	
Enter the TRIAL ID number	1 ENT		[ ]

2. IN FLIGHT (Daylight conditions only)

NOTE: These tests may be carried out in any order, but enter the designated ID

ROTOR TRACK & BALANCE – STEADY STATE (RSS) — RSS

Using the same procedure described above, initiate data acquisition at the following conditions. Enter the appropriate TRIAL ID number when each analysis is complete:

TRIAL ID 2.	HOVER	[ ] ENT	[ ]
	(Note that a ROTOR TRANSIENT (RTR) test is required during a take–off – see 3 below)		
TRIAL ID 3.	70 KNOTS DESCENT AT * [ ] DEGREES COLL PITCH		[ ]
	(* Carry out at any convenient pitch setting and enter value in box)		
TRIAL ID 4.	100 KNOTS STRAIGHT AND LEVEL		[ ]
TRIAL ID 5.	130 KNOTS & 15.5 DEG. CP (IN DESCENT IF NECESSARY)		[ ]
TRIAL ID 6.	NOT REQUIRED		[ ]

3. DURING THE TAKE–OFF (AIRFIELD OR OFFSHORE) (Daylight conditions only)

ROTOR TRANSIENT (RTR)

As the take–off is initiated, press: RTR [ ]

Display will indicate when data acquisition has been completed (after approximately 30 seconds)

ACTIONS REQUIRED TO EXECUTE DATA ACQUISITION – Carry out the following tests in any convenient order:

ACTION	KEY PRESS REQUIRED	SCREEN DISPLAY	TICK WHEN COMPLETED
4. IN FLIGHT			
DYNAMIC CONTROL LOAD MEASUREMENT (DCL) Establish the following flight condition: STRAIGHT & LEVEL – 62% COMBINED TORQUE		ENTER STRAIN GAUGE NUMBER FOR DCL ANALYSIS (1 – 8) >>>	
Press DCL:	DCL		
Select the designated strain gauge:	[ ] ENT		
On completion of data analysis, this screen will appear:		DYNAMIC CONTROL LOAD ANALYSIS COMPLETE READY	☐
5. IN FLIGHT			
GEARBOX VIBRATION (VIB) Establish straight and level flight using 62% torque – press VIB:	VIB	VIBRATION ANALYSIS RUNNING ACQUISITION IN PROGRESS READY	
After approximately 15 seconds, the STATUS page will appear and show 'VA ACQUIRING'		Screen reverts to STATUS page: VA ACQUIRING	
Maintain flight condition for approximately 3 minutes until this display appears: NOTE: Subsequent processing of the gearbox vibration data will take up to 20 minutes during which time the battery must not be switched off. STATUS page will show ' VA PROCESSING'		VIBRATION ANALYSIS RUNNING PROCESSING DATA NOW READY	☐

6. ON THE GROUND JUST PRIOR TO SHUTDOWN

** IMPORTANT DATA WILL BE LOST UNLESS LIFE USAGE IS DE–SELECTED BEFORE AC POWER IS LOST **

THE FOLLOWING ACTIONS ARE VITAL:

Select life usage OFF: LOF

Wait 5 seconds before switching the alternators OFF or retarding the SSL's.

COMMENTS:____

APPENDIX B

SWANSEA TRIBOLOGY CENTRE REPORT

SWANSEA TRIBOLOGY CENTRE

R.P.D. ANALYSIS REPORT

Slide No. 152 Date 15.2.90

Organisation Bristow Helicopters Limited, Aberdeen Sample No. 01/90

Equip. Type G-TIGW Serial No. Operating Time

Sample date 9.2.90 Oil Type Time on Oil

Other Data MGB S/N M453

Volume of Sample Processed 2 mls P.Q. Index 9 (Pot Method)

Types of Particles	None	Few	Moderate	Heavy
Normal Rubbing Wear/pitting		←-----	-----→	
Fatigue Chunks (Typical gear surface fatigue)	←-----	-----→		
Spheres (fatigue cracks in rolling bearings)	←-----	-----→		
Laminar Particles (gears or rolling bearings)	✓			
Severe Wear Particles	✓			
Cutting Wear Particles (high unit pressure)	←-----	-----→		
Corrosive Wear Particles	✓			
Oxides Particles (includes rust)	✓			
Dark Metallo-oxide Particles (typical hard steels)	✓			
Non-ferrous Metallic	←-----	-----→		
Non-metallic, Crystalline	✓			
Non-metallic, Amorphous (eg. friction polymer)	←-----	-----→		

Comments: Low/medium density deposit. The majority of particles present were normal rubbing/pitting wear ranging in size up to ~40μm but generally <15μm. Some fatigue like chunks (up to ~55μm) spheres (<10μm) and cutting wear (up to ~50μm) also present. Occasional particle exhibited evidence of localized heating (blue colour). The non-ferrous metallic were pale yellow coppe containing particles (bronze) ranging in size up to ~65μm but generally <15μm. The wear rate is higher than normal and the wear situation is considered to be normal/caution.

Considered Judgement of Wear Situation:

	Very Low	✓	Normal	✓	Caution		Very High (Red Alert)

DAILY OPERATION - HUMS AIRBORNE SYSTEM

Daily Operation

The following was a typical daily itinerary for data acquisition using the HUMS Airborne System.

1. The Engineering staff dedicated to the HUMS programme annotated the pro-forma (re. Appendix A), which was used to define the specific conditions required for each flight.

2. The pro-forma was inserted in the relevant aircraft technical log.

3. The pilot familiarised himself and his co-pilot with the requirements on the pro-forma prior to boarding the helicopter.

4. The pilot initiated the data acquisition, using the CDU, as requested and completed the pro-forma.

5. The pro-forma was returned to the Engineering HUMS office.

6. At the end of the days flying an engineer downloaded data from the health monitoring computer (S.I. 0854 KEL) onto a floppy diskette using a portable, lap top computer as a DTU.

   Having collected the equipment (Computer, RS232 cable and formatted diskette), the engineer then had to locate the aircraft, to which he would have to supply ground power (to avoid draining the aircraft batteries). It was sometimes necessary to reposition the aircraft to achieve this.

   A full uninterrupted download of the S.I. 0854 KEL computer took approximately 15-20 minutes and then a further 5 minutes to download the Ferroscan (Sensys) system. Unfortunately aircraft power supply, partly formatted diskette, data checking process, RS232 link, etc. could and did interrupt the download, necessitating re-start. Taking all the problems and physical actions into account a typical download took between 1 and 1½ manhours each on two aircraft daily.

7. The Engineer returned to the HUMS office and loaded the data into the ground based computer using the floppy diskette.

8. Engineering staff made archive and working copies of the data onto floppy diskette using the ground based computer. The HUM staff in Aberdeen were responsible for viewing the downloaded data, investigating any problems highlighted by the data and advising interested parties.

9. Working copies of the data were posted to relevant parties.

Note:- If the pilot had not carried out the correct procedures it was possible that the data stored was that recorded on a previous flight and still held in non-volatile storage. This meant that it was possible to spend a lot of time downloading the wrong data!