PAPER Nr.: 116

A REVIEW OF TRANSMISSION VIBRATION MONITORING AT WESTLAND HELICOPTERS LTD

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OCTOBER 4 - 7, 1994 AMSTERDAM

Printed by the Technical Highschool Haarlem

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ABSTRACT

WHL have had many years of experience with the application and development of vibration analysis techniques to improve the health monitoring of helicopter transmissions. Originally targeted at transmission rig testing in the 1960's the techniques have been progressively developed to a stage where they are now used routinely as part of integrated HUM systems on many types of in-service helicopter.

The technique development process has been heavily dependent upon the availability of an expanding database of transmission monitoring experiences in the rig and aircraft environments. Many novel additions or amendments to established algorithms have been, and are still being tried. Whilst these can appear very efficient in specific instances of transmission malfunctioning, few survive exposure to tests on the wide range of archived data.

In recent times, there has been an increasing need to demonstrate technique reliability and effectiveness to regulatory as well as commercial organisations. This has involved the monitoring of fatigue crack growth in a range of components within a helicopter gearbox under representative aircraft conditions. It is important that monitoring systems respond unambiguously at an early enough time to enable the pilot or maintenance personnel to take appropriate actions.

1. INTRODUCTION

Helicopter manufacturers are under increasing pressure to improve the safety and reliability of their products. Airworthiness authorities require helicopters to approach the safety standards already being achieved by fixed wing aircraft and market pressures demand that this is achieved with minimum effect upon, or preferably with a reduction in, the cost of ownership.

Naturally, the rotor drive system is one of the elements of a helicopter that is under scrutiny, both from the design point of view and the methods employed to monitor condition in service. With respect to the latter, more effective monitoring methods could lead to an earlier and more precise identification of component distress. This would not only benefit flight safety but also introduce opportunities for improving the maintenance strategy.

This paper focuses attention on one of the monitoring techniques that is starting to receive universal acceptance as a valued complement to conventional monitoring methods, the vibration health monitoring (VHM) of gearboxes and associated transmission components.

It has been known for a long time that the vibration produced by a gearbox can be analysed to yield information about the condition of its internal gears, bearings and shafts. Less well publicized has been the enduring difficulty of segregating and quantifying that vibration information which is specifically related to a type and severity of component damage. The discussion to follow illustrates how Westlands have addressed this difficulty and in so doing have matured their technology so that VHM is now used in an executive capacity to reject defective transmission components in both rig testing and on the aircraft.

2. EARLY VIBRATION MONITORING STUDIES AT WHL

By the late 1960's WHL were routinely conducting narrowband frequency analyses of gearbox vibration as a means of identifying component distress in gearbox fatigue and endurance testing. The confidence to terminate testing and prompt a strip examination was founded on experiences with earlier test cases and vibration analysis of deliberately seeded faults in gears and bearings.

Through the 1970's the quality of the frequency analysis equipment improved but despite efforts to automate or 'simplify' the analysis process, the success of the procedure remained heavily dependent upon the expertise of the analyst. Such techniques as plotting the side-band behaviour about the gear meshing frequency and its harmonics produced reliable trend information for certain categories of gear and shaft faults but the analysis and plotting equipment remained laboratory based, using tape recordings of accelerometer signals gathered at the test site.

Time domain portrayals of gearbox vibration using a 'raster' technique provided a visual means of enhancing, and locating to a shaft, the source of a gear defect.

In the late 1970's proprietary frequency analysis equipment was replaced by a digital computer based system. This immediately introduced a step change in processing flexibility and in particular provided an opportunity to exploit the long established synchronous time averaging (signal averaging) process.

3. DEVELOPMENT OF THE PRESENT VHM CAPABILITY

Although commercial software packages were available to perform basic functions of data acquisition, processing and display, it was soon realized that only self-written routines and command structure would provide the necessary combination of flexibility and control. The strategy has persisted of having default or 'aircraft standard' solutions for the use of 'non-experts' when analysing vibration data for authentic health monitoring purposes and high flexibility when developing and evaluating new routines.

Only after exhaustive testing and evaluation are new or revised techniques integrated into the 'aircraft standard' software set. The techniques are exposed to the data-base of vibration recordings from gearboxes in various states of health in rig tests and on the aircraft and they have to demonstrate not only a high and consistent response to the defects at which they are targetted but a high resistance to the misinterpretation of other conditions (low false alarm rate).

The capability of the analysis process has expanded to satisfy the expectations of test engineers for greater sensitivity to an increasing range of failure conditions, and increasingly, the requirements of different operators when monitoring the transmissions of their helicopters in service.

3.1 THE WHL TRANSMISSION VIBRATION DATABASE

As implied above, Westlands regard their continually expanding data base of analogue transmission vibration recordings as an indispensable archive of information for the development and evaluation of techniques. The data base has been accumulating for over 20 years and includes comprehensive coverage of nearly all of the gearbox development testing at WHL over that period. Fatigue and 'oil loss' tests have obviously been the most productive sources for the myriad of examples of progressive and sudden component failure modes.

From the early 1980's there has been an expanding data base of analogue vibration recordings, and digitally processed data, from the transmissions of in-service civil and military helicopters. A major portion of the data comes from helicopters not manufactured by WHL.

Analogue recordings and pre-processed data from the aircraft are of vital importance when fine-tuning algorithms for sensitivity under conditions of 'normal variability'. They also present cases of degenerated or corrupted signals that have to be expected and accommodated in 'real-life' monitoring situations.

Data-handling routines have been developed to enable health monitoring algorithms and thresholds to be subjected to a group of test cases from the archive with the minimum of human interaction.

4. THE BASIC VIBRATION ANALYSIS PROCESS

4.1 DATA ACQUISITION

Transmission vibration is usually monitored by accelerometers mounted at strategic locations on the gearbox casings [see figure 1]. These locations are established after a consideration of the internal geometry of the gearbox and then experimental optimisation to achieve high quality signals from all target components with the minimum number of transducers. One or more shaft speed reference (azimuth) signals are also required.

4.2 DATA PROCESSING

Signal quality or 'integrity' checks are implemented on the digitized raw vibration signals and at other stages in the processing network. The network manipulates the signals in different ways depending on the component and the component defect mode being investigated [see figure 2].

GEAR AND SHAFT DEFECTS

These are investigated using the well-known process of synchronous time averaging (signal averaging). The process 'averages out' constituents of the gearbox vibration signal that are not synchronous in frequency with the particular gear shaft being analysed. Information relating to the cyclic behaviour of the target shaft, and any gear on that shaft, is not degenerated by the averaging procedure and so can be studied for defect information against a now very low level of background 'noise'.

Gear tooth defects are often masked by regular meshing effects in the signal average. Therefore an enhanced form of signal average is generated where only vibration components relating to differences in the meshing action from tooth to tooth are retained [see figure 3].

Various health monitoring parameters are calculated from the distribution of points in the enhanced signal average and these parameters are interpreted in combination via a 'fault matrix' to identify the type and severity of gear tooth distress.

Fatigue cracks in gear shafts and gear webs will invariably change the torsional stiffness of the assembly. This is conveniently detected by utilising changes in the frequency spectrum of the signal average. Different groupings of shaft rotational orders will respond to different crack geometries and health monitoring parameters have been developed to identify the type and severity of emerging forms of distress.

BEARING DEFECTS

The vibrational disturbances generated by defects in rolling contact bearings are only loosely repetitive in time and character. Defects on the rotating elements will contact at varying spatial distances and orientations with respect to both the vibration transducer and the applied load, and with a progressive and complex lag as a result of sliding or 'slip' of the rolling elements.

An analysis process is used which accepts unstable behaviour but emphasizes disturbances in motion by the removal of uninformative constituents of the total vibration signal, including of course the vibration at frequencies associated with the regular meshing action of gear teeth. The nature and severity of any bearing distress is assessed using parameters which describe features of the 'enhanced' vibration signal.

DEFECTS OF OTHER TRANSMISSION COMPONENTS

A library of routines have been developed to accommodate the monitoring of less frequently encountered components or component applications as well as ancillary transmission items such as lubrication and hydraulic pumps and the rotating elements of oil cooling systems.

5. VIBRATION HEALTH MONITORING IN PRACTICE

5.1 HEALTH MONITORING OF RIG TESTS

Versions of the WHL VHM analysis suite are installed in computers at gearbox and gearbox component test sites. These are pre-configured to be used by 'non experts' or to form part of computerized rig control systems. In both cases testing is terminated when parameters exceed predetermined thresholds. Applications range from gear test machines to complete transmission systems such as the EH101 in the computer-controlled Universal Transmission Test Rig facility.

5.2 VHM TECHNOLOGY STUDIES

A number of studies have been conducted in order to advance the technology and demonstrate the capability of transmission vibration monitoring. These have involved the testing of gearbox components and assemblies when manufactured and assembled to the extremes of production tolerances and beyond, as well as components with deliberately induced weaknesses and modes of distress.

WHL are working with the civil and military authorities (CAA & MoD) to demonstrate the effectiveness and limitations of vibration health monitoring when applied to helicopter transmissions. The issues currently being addressed include the 'visibility' of potentially critical defects at normal aircraft operating powers and the flight time available between the positive identification of critical defects and the aircraft becoming unsafe to operate. Some examples of recent and current studies are briefly mentioned below.

LYNX MAIN ROTOR GEARBOX

Crack initiation sites were introduced into the gearbox output (conformal) wheel. Fatigue cracks were propagated by testing at normal aircraft powers. Vibration recordings were gathered during the test and borescope inspections were used to maintain a history of crack growth. Figure [4] shows the enhanced signal averages of conformal wheel shaft vibration and corresponding crack size at stages throughout the test. The first indication of the presence of a defect was approximately 113 hours before the end of the test, or over 200 hours of normal aircraft operation. It should be noted that the gearbox was still operating normally at the end of the test and a high aircraft-representative power had to be employed in order to sustain crack growth.

S61N MAIN ROTOR GEARBOX

WHL are conducting a series of crack propagation tests on selected components within the gearbox, again introducing local flaws to achieve the target modes of failure at aircraft-representative powers. The results of vibration analyses are being correlated with actual damage as above.

5.3 AIRCRAFT MONITORING

VHM techniques can perform impressively in the controlled environment of rig testing but care is required to achieve the necessary consistency and effectiveness in the real and sustained aircraft situation. WHL's approach from the outset has been one of caution, not raising the user's expectation above that which can be demonstrated by tests on archived data and tests on lead data from the actual application. This strategy has been maintained from the early 1980's through a series of trial and bona-fide applications. Some of these applications are mentioned below.

5.3.1 APPLICATION TO WHL AIRCRAFT

WESTLAND 30-100 VHM

A comprehensive health monitoring system was required for Westland 30-100 in order to permit a rapid but safe increase in the 'Time Before Overhaul' (TBO) period of the transmission. This included a requirement for a vibration-based method to identify instances of pending gear tooth fatigue and to assist with identifying other forms of component distress that might not produce metallic debris adequate for detection purposes. An appropriate VHM system was designed and tested and introduced into commercial use in the Spring of 1982. This was the first example of an advanced transmission VHM system being used as an integral part of a helicopter maintenance strategy.

Gearbox vibration recordings were extracted from the aircraft at 100 hour intervals and returned to WHL for rapid analysis on a ground station, using pre-defined algorithms and thresholds. Recordings were regularly received from 17 aircraft based in the UK and US and for a period in excess of 30,000 flying hours. One case of gear tooth pitting and one case of tooth fracture occurred and both were detected using M6*, the VHM parameter utilised for the detection of localised gear tooth defects. There were no other instances of gear tooth distress and the VHM system did not produce any false 'red' alerts [see figure 5].

Later in the monitoring programme the ground based algorithms were embodied in a prototype integrated on-board HUM system for the Westland 30-300 helicopter and in a prototype portable Vibration Analysis System (VAS) for the Westland 30-100 helicopters. Had the Westland 30 helicopter variants continued in production, operators would have had the opportunity of gathering and processing data during ground running or in flight without recourse to tape recording and processing away from the aircraft.

LYNX VHM TRIAL

The UK Army and Navy wished to assess the feasibility of using portable VHM equipment in the military environment. The Westland 30-100 'VAS' design was suitably modified and a small batch of prototype VAS units were produced to supply to Squadrons operating Lynx Mk1 and Mk3 helicopters. PC-based ground stations were also supplied to enable further processing of data gathered on VAS to the stage where a 'condition report' was presented to the maintenance engineer. Vibration samples were gathered every 25 flying hours from 8 Army and 8 Navy Lynx, both in ground running and in flight.

Valuable experience was gained by all concerned. The Services had varying degrees of success in installing and maintaining their own aircraft instrumentation and there were logistic difficulties in too frequently taking samples with the VAS. The ground station was found convenient and easy to use.

EH101 HUMS

The EH101 will have a fully integrated HUM system but with flexibility in the design of the on-board and ground station functions to suit the needs of military and civil customers.

Agusta have responsibility for the design of the transmission system and its health monitoring needs. WHL are assisting with the development of the VHM system as required. WHL are monitoring the UK-based development aircraft with their suite of algorithms and thresholds, using analogue recordings of gearbox vibration taken at 5 hour intervals.

5.3.2 <u>TRIALS ON NON-WHL AIRCRAFT</u>

Developments of the Westland 30 VAS and the Westland 30-300 integrated system formed the basis of trials on Super Puma helicopters in commercial operations over the North Sea and on a Sikorsky SH-3H operated by the US Navy from NAS Jacksonville.

ECF SUPER PUMA MK I

The Super Puma trial was instigated by the CAA and conducted and part sponsored by Bristow Helicopters Ltd (BHL). CAA had previously expressed their concerns over helicopter safety in the 'HARP' report (Reference 1).

Five Super Puma's were monitored, primarily in flight. Analogue vibration recordings were taken for a period in excess of 6500 A/F hours, followed by down-loads from the on-board systems into a local ground station for a further 6122 A/F hours. Three aircraft shared a portable VAS and two had permanently installed processors. The downloads from both system configurations consisted of signal average files plus computed parameters for the identification of an extended range of gear and shaft defects. Instrumentation integrity checks were also incorporated.

The trial successfully demonstrated that a vibration health monitoring system could be operated and maintained in a commercial helicopter environment, and that reliable diagnostic information could be produced. The trials also identified key features necessary for a practical vibration health monitoring system:-

i) There should be a minimum of pilot involvement in the acquisition of data.

ii) The system should be easily reconfigurable for use on different helicopter types when an operator has a mixed fleet.

iii) The system should generate unambiguous diagnostic outputs and advise appropriate maintenance actions.

iv) The system should be capable of being operated by engineers/technicians with the minimum of training and 'expert' back-up.

v) The instrumentation system should be designed to withstand the rigours of the operating environment and installation integrity checks should be regularly implemented.

SIKORSKY SH3-H

The US Navy trial had similar objectives to the Lynx 'VAS' trial but on 1 aircraft and over a more restricted flying period (233 A/F hours). The system had the additional feature of a pilot warning facility. As well as demonstrating the consistency of the VHM algorithms and thresholds, the trial confirmed that the system, including the ground station, could be installed, maintained and operated at squadron level.

5.3.3 COMMERCIAL IMPLEMENTATION OF TRANSMISSION VHM

IHUMS I

In 1989 the CAA made it mandatory for all helicopters exceeding 2730 Kg to carry a flight data recorder (FDR).

Encouraged by the results of the Super Puma trial, BHL saw the potential and cost advantage of designing an Integrated Health and Usage Monitoring System (IHUMS) to interface with an FDR. An IHUMS 'team' was formed with GEC-Marconi producing the acquisition unit, WHL supplying transmission VHM algorithms and procedures and MJA Dynamics supplying the rotor track and balance (RTB) diagnostics.

The core transmission VHM algorithms are common to all helicopter types, type information being loaded from a portable variant of the ground station. The VHM techniques have been further extended to encompass bearing defects. Partial data processing is carried out on the helicopter and vibration data stored for processing in the ground station. Vibration data is archived as an indispensable aid to the development and enhancement of facilities.

IHUMS I gives a maintenance message showing transmission status and any action required of the ground crew [see figure 6]. No expertise in VHM is expected although extensive facilities exist within the system to view the signals and parameters.

The IHUMS I system is being used by 6 commercial operators world-wide on 97 helicopters and monitoring experience has exceeded 100,000 A/F hours. Nine different helicopter types are involved. Several of the malfunctions that have been flagged and subsequently rectified would have escaped detection by non-vibration based procedures.

IHUMS II

The second generation of IHUMS (IHUMS II) is now under development and it has already been selected by Sikorsky for the S76C and S92 aircraft.

IHUMS II builds on the principles of IHUMS I and includes airborne implementation of the WHL transmission VHM procedures with pilot alerts as appropriate. Enhancements to the epicyclic processing and bearing analysis have been included.

6. DEVELOPMENT OF TECHNIQUES

Experiences with the performance of VHM techniques in practice have naturally inspired experimentation with enhanced and alternative methods of signal processing. This has led to a library of 'special purpose' routines that can be utilized when formulating new or revised strategies. An example of this is the re-use of a technique developed at WHL in the mid 1980's for 'freezing' the motion of epicyclic assemblies. Not necessary for the enhancement of defects in all designs of epicyclic assemblies, it has been re-employed to benefit the capability of IHUMS II.

More recent research and development activities include:-

1) A method of feature suppression/compensation to remove the influences of those gearbox manufacturing deviations that are within production tolerances but which would otherwise degrade the efficiency of fault detection. A procedure is in the final stages of qualification testing.

2) Improvements to the signal average enhancement process in order to maximise the 'visibility' of impulsive gear meshing behaviour.

3) The use of Artificial Intelligence to better define the boundaries of unacceptable behaviour in the multi-parameter 'fault matrix'. This is in addition to experimentation with neural networks as an alternative to algorithm-based methods of condition assessment.

4) Advanced methods for data integrity checking.

As well as R&D activities within the Company, WHL have collaborated with other companies for example when co-ordinating the CEC-BRITE EURAM research programme into advanced helicopter HUM systems. Another example was the supply of vibration data and analysis results to the US Navy after testing a CH46 aft rotor gearbox in a WHL test facility. The gearbox in question was assembled with a sequence of defective components, both from service and artificially induced.

7. CONCLUSION

The vibration health monitoring of helicopter transmissions has evolved at WHL from an interesting research activity to committed systems on production helicopters.

VHM can identify the actual components of concern within complex assemblies, and also identify failure modes such as fatigue damage which issue little or no debris for detection by other means.

By maintaining a close relationship with commercial operators, certification and military authorities, it has been possible to implement a strategy of VHM design and development based on need and with a control on the enthusiasm for 'novelty'.

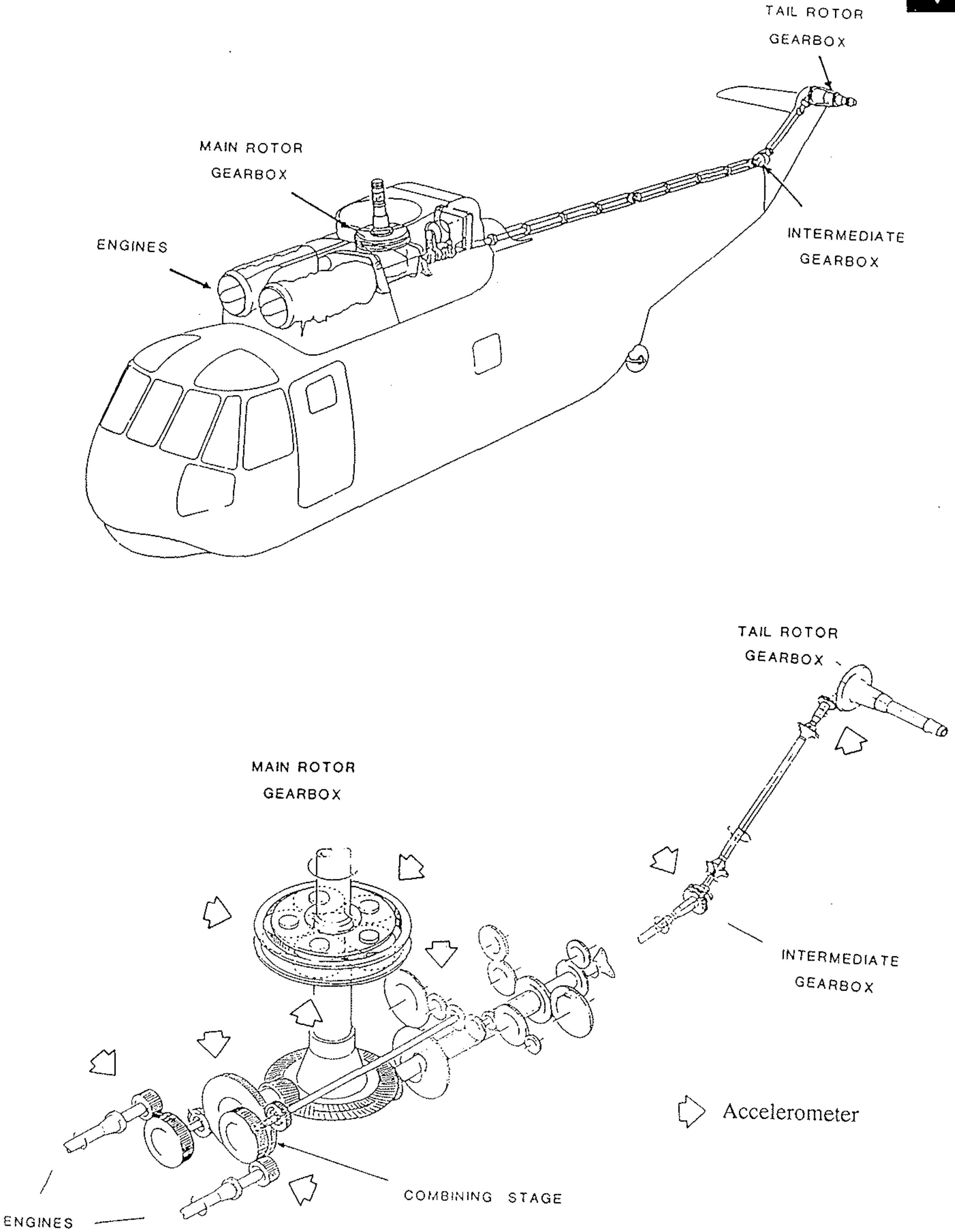
Whilst WHL are always receptive to proprietary health monitoring devices, the VHM process is so intimately involved with the design and performance of the product being monitored that general 'machine monitoring' solutions have little relevance to the sophisticated and critical helicopter environment.

8. ACKNOWLEDGEMENTS

The authors wish to acknowledge the encouragement and support given them over a long period by operators and other authorities, particularly BHL, UK MoD and CAA.

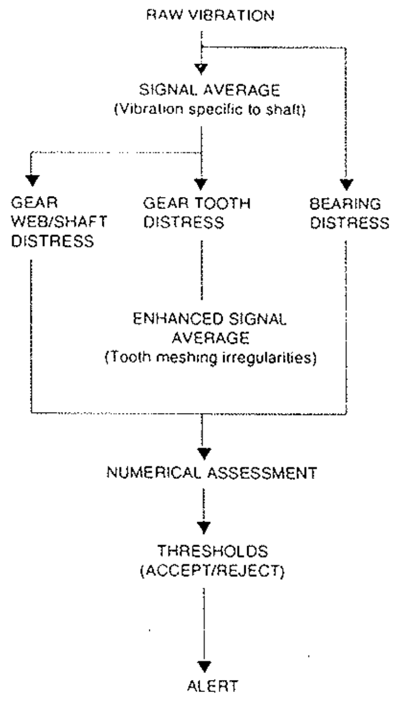
9. REFERENCES

1. CAA 'Report of the Helicopter Airworthiness Review Panel'
CAA Document CAP 491, June 1984.



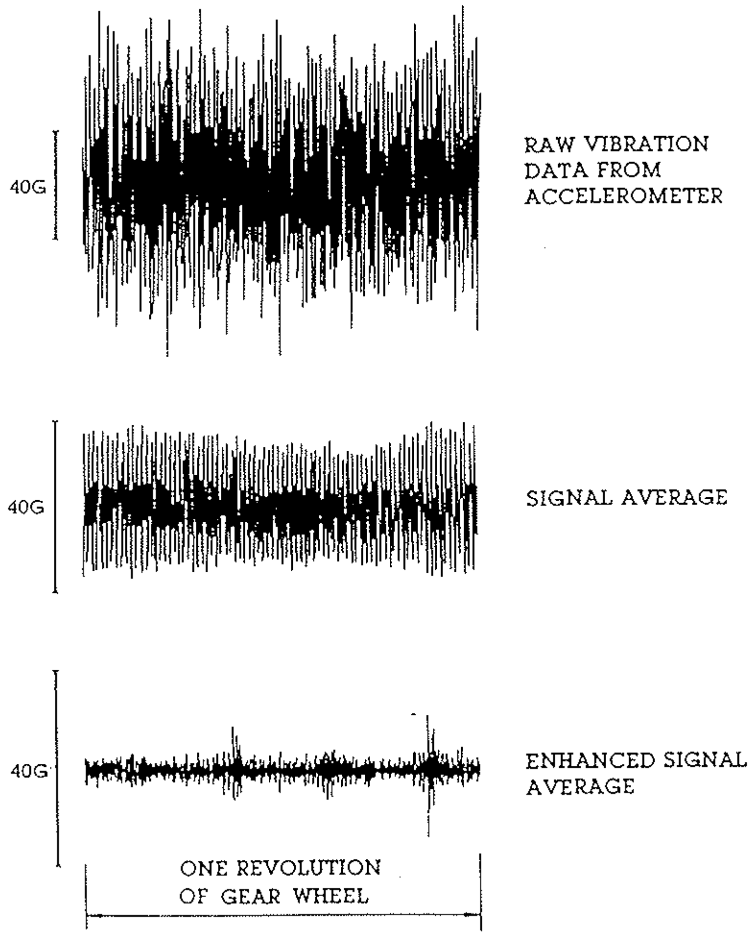
TYPICAL ACCELEROMETER ARRANGEMENT

Figure :- 1



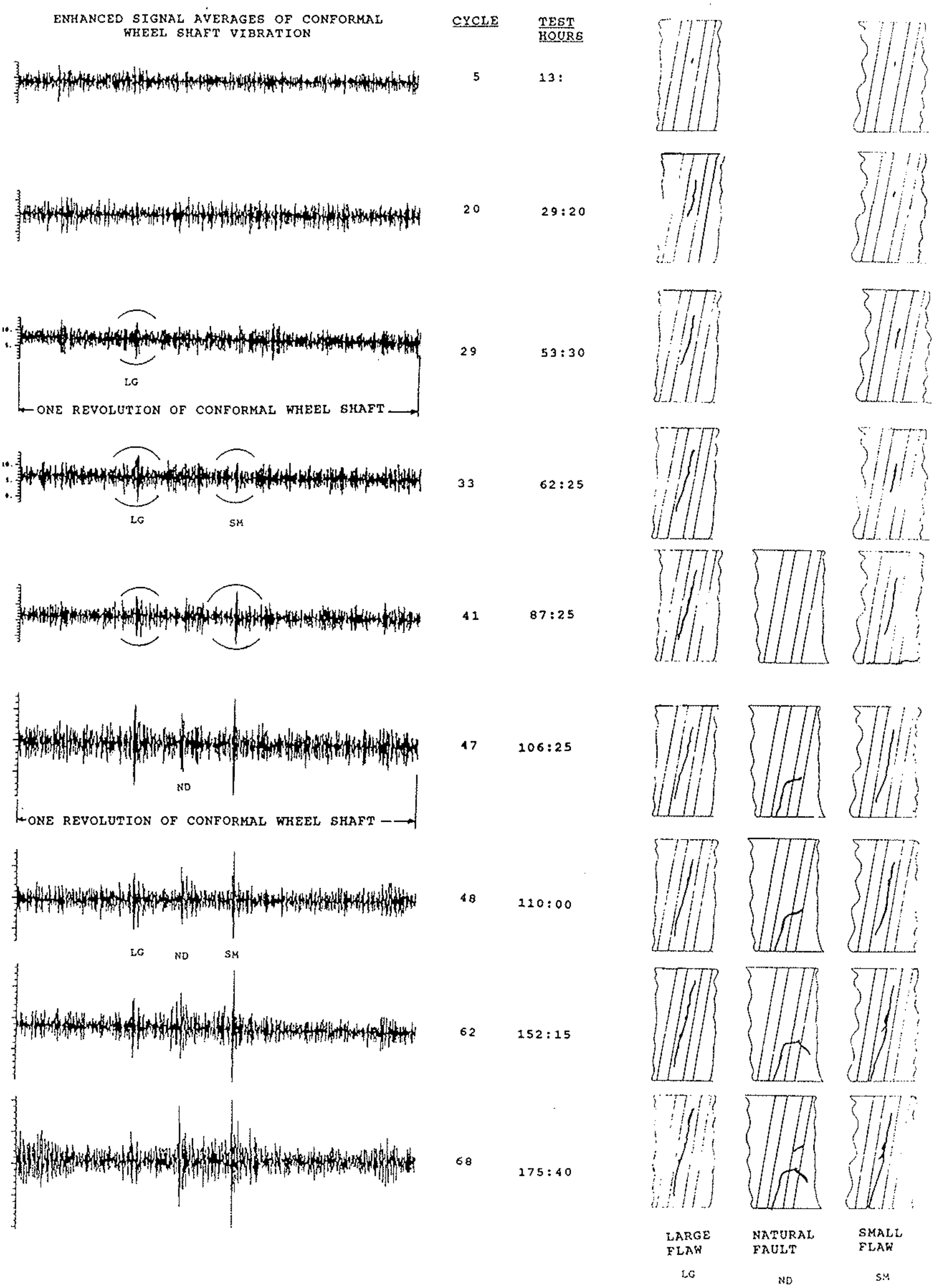
PROCESSING NETWORK
FOR GEAR, SHAFT
AND BEARING DEFECTS

Figure :- 2



ENHANCED SIGNAL AVERAGING

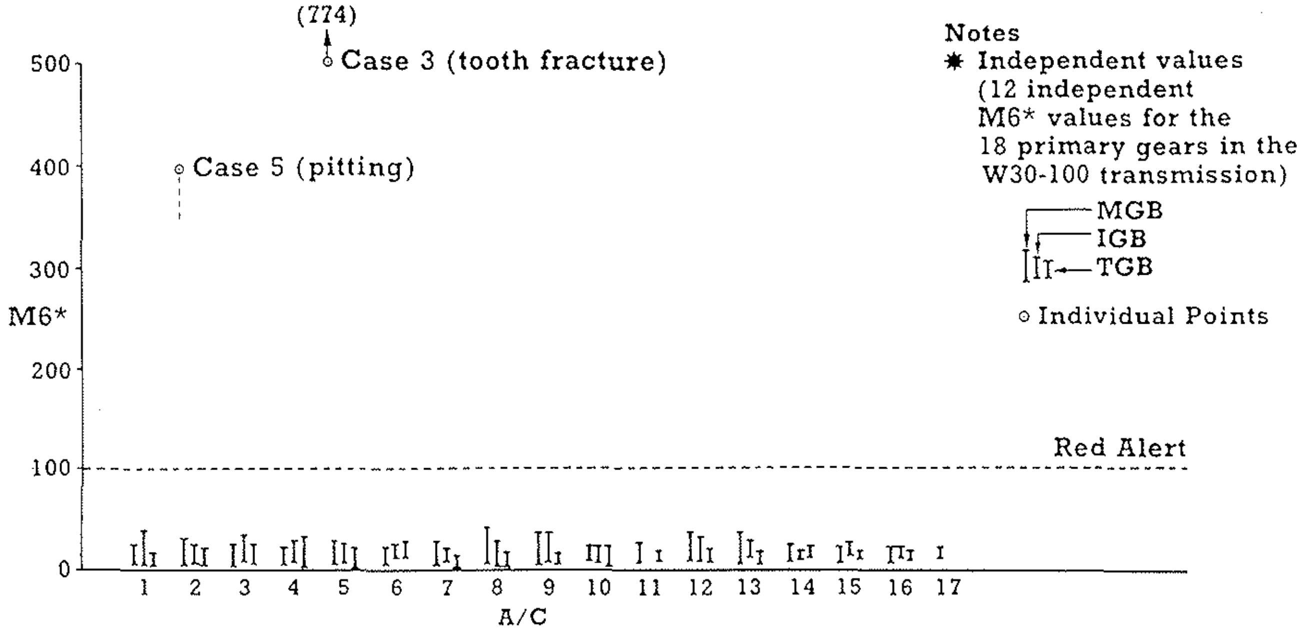
Figure :- 3



CORRELATION BETWEEN VHM RESULTS AND FATIGUE CRACK LENGTH

Figure :- 4

Range of M6* values
(with high value cases segregated)
From 17 aircraft & over 30,000 A/F hours



EXAMPLE OF VIBRATION HEALTH
MONITORING PARAMETER RESULTS

Figure :- 5

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IHUMS Log Report - Page 1
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(Printed by Program Release 81.60)

Log Number   : 2608A  15/02/93
For          : G-TIGP (AS 332 L1)
Mod. State   : 3S (136)
Flight       : 49A
Captain      : LYONS
Co-Pilot     : BIRD

Usage Data
==========
```

Sector	-001-	-002-	-003-	-004-
From	EGPD	SSUPP	EGPD	SSUPP
To	SSUPP	EGPD	SSUPP	EGPD
Start Taxi	6:52	-	10:00	-
Take Off	7:00	8:21	10:03	11:14
Land	8:00	9:40	11:02	12:33
End Taxi	-	9:43	-	12:40
Shutdown	-	-	-	12:41
Sector Time	1:00	1:19	0:59	1:19
Landings	1	1	1	1
No. of Pax	16	19	14	16
Pax. Wt	2992	3553	2618	2992
Baggage	520	644	425	505
Cargo	41	10	0	0
Fuel	3150	2200	3500	2300
Z. F. Wt.	12254	12254	12254	12254
Total Wt.	18957	18661	18797	18051
Fuel Uplift	L1151	L 205	L1710	L 0
Full Cycles	1 1	0 0	0 0	0 0
Part Cycles	0 0	0 0	0 0	0 0
Dry Cycles	0 0	0 0	0 0	0 0
Pumps Off	0 0	0 0	0 0	0 0
IntCon Eng1	0	0	0	0
IntCon Eng2	0	0	0	0
Max. Con.	0 0	0 0	0 0	0 0

```
Arrival Fuel back at base = 900

    Hours B/fwd = 12265:48
Flight Duration = 4:37
    Hours C/fwd = 12270:25
```

```
Exceedences and IHUMS Defects
=============================

 1. IHUMS Transmission Defect Found.
    Localised Gear defect level 2.
    Accelerometer: #3 (# 1 Accessory Drive (Port)).
    Channel: 63-25-30 Port Hydraulic Idler.
    Work Card No: 1000101.
    No previous defect.

   <End of Log Sheet 2608A>
```

IHUMS I POST FLIGHT
HELICOPTER STATUS REPORT

Figure :- 6