EIGHTH EUROPEAN ROTORCRAFT FORUM

Paper No: 7.3

HEALTH MONITORING OF HELICOPTER GEARBOXES

D.G. ASTRIDGE

WESTLAND HELICOPTERS LTD, ENGLAND

August 31 through September 3, 1982

AIX-EN-PROVENCE, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

HEALTH MONITORING OF HELICOPTER GEARBOXES

D.G. Astridge

Westland Helicopters Ltd.

1. SUMMARY

The various problems posed for gearbox health monitoring are discussed, and the solutions applied to the Westland 30 helicopter are described. These embrace the transition from traditional, well known laboratory based techniques and subjective evaluations, to the on-line facilities of future aircraft such as the EH101, and growth versions of Westland 30.

2. INTRODUCTION

The very much higher usage rates and longer lives required for civil helicopters dictates that transmissions be removed 'on-condition' i.e. when health monitoring techniques determine that continued operation could prejudice flight safety, or result in expensive secondary damage. Whatever techniques are employed, they must be capable of indicating this event with 100% certainty, with very low incidence of erroneous or premature indications; and be early enough to permit planned removal. Most gearboxes contain main shaft bearings which have finite contact fatigue lives, and many contain gears with lives limited by bending or contact fatigue. Traditionally gearboxes have declared safe-lives and specified times between overhaul (TBO) established by rig tests, aircraft ground running and flight test, and by inspections of sample gearboxes in service. The scatter on fatigue lives is such that methods of failure detection are required in addition to any provisions that may be made for monitoring load exposure. The latter is useful for improving operational procedures where possible, rostering of aircraft to obtain even usage where a fleet covers different operations, and for long term planning of removals and inventories. It is considered that the health monitoring techniques traditionally used - Spectrographic oil analysis and magnetic plug inspections are not totally adequate, and must in time be replaced by techniques which can satisfy the above targets and impose a smaller maintenance workload.

3. THE PROBLEMS FOR MONITORING SYSTEMS

3.1. Failure Modes and Rejection Requirements

It is necessary to establish for each component in a gearbox the possible modes of degradation, and the point at which operation should not be allowed to continue. The rejection criteria are quite different to those applied at overhaul inspections, where the concern is to establish a build standard that will survive 2000 hours, or whatever the TBO happens to be. It is not always possible to read across experience from one gearbox design to another - differences in contact conditions (rolling/sliding speeds, oil, temperature, load, filtration standard, surface finish/treatment), gearcase deflections, materials, operation and maintenance, and other factors, may result in different defect manifestations. In addition, highly stressed gears and bearings require the highest strength steels, with a degree of processing and manufacturing control from ingot to finished component that is extremely demanding. It is not unknown for problems to arise which are restricted to batches of components - health monitoring systems must be able to respond to defects which 'come and go' without additional development. As an example, the generalised development of failure modes in helicopter gears is sketched in fig.1. Inevitably some degree of microcracking occurs on the surfaces of highest quality gears, and from these, micropits tend to form on working surfaces, often in dedendum regions, but not exclusively (ref.1). They spread to form an area having a frosted appearance, and the phenomenon is variously known as frosting, grey-staining, or micropitting. The pits are so small - a few microns across - that they often appear on the crests of ground surface finish lines, and have the characteristic shape and propagation features of large scale fatigue pitting. In some cases micropitting may remain innocuous throughout the safe life period of a gear; in others slow progression to larger fatigue pits occurs; and in others the damage progresses very rapidly, modifying the involute profile and resulting in either scuffing or erosion - gross disruption of profile causing a detectable increase in noise levels. Factors influencing which form of progression the damage will take include all those relating to contact phenomena listed above, a grossly phosphate etched surface being particularly bad. That good surface separation is beneficial is evidenced by the lower propensity of conformal tooth forms to micrpitting, and areas where is has occurred tends to line up with the thinner film thickness regions. With involute tooth forms there have been instances of further pit development to the point where large chunks of tooth have been released, and where cracks have propagated into the tooth roots resulting in complete fracture. In overload tests there have been cases where the crack has propagated into the gear rim, releasing a number of consecutive teeth, and completely fracturing the supporting web, resulting in loss of drive. The same potentially catastrophic result can arise via the scuffing/rapid erosion route where severe modification of the involute profile results in very high contact stresses.

Lubrication system failures, or blocked jets can also cause problems, even though modern gearboxes such as Lynx have demonstrated good endurance at cruise powers even following complete loss of oil - overheating and softening will nevertheless lead to premature failure. Errors in manufacture or build can result in increased contact stresses causing premature surface fatigue, or in geometry errors particularly at the edges of working flanks, producing scuffing.

At what stage in the damage development should a health monitoring system raise a flag? Clearly the consequences of rim failure are so potentially disastrous, however remote the liklihood, that an HM system should be capable of flagging it with 100% certainty, and with very fast response. At the other extreme, does an operator really need to be aware of benign micropitting, or of self-healing scuffing? Any significant build errors or lubrication system problems should, of course, be rectified immediately. Deterioration occurring in internal components during service cannot normally be corrected prior to gearbox strip (possible exceptions being improvement of filtration standard, or change of oil type, where already substantiated) - the event that an operator is trying to put off for as long as possible. Although grateful for advanced warning sufficient to plan a gearbox removal to minimise inconvenience, he will only be interested in indications which have a good correlation with damage progression and rejection criteria.

WHL experience with fault detection in gears in all gearboxes is also summarised in fig.1, the capital letter codes associated with each damage condition representing the best technique as currently developed. These will be discussed in more detail later.

HM techniques appropriate to degradation patterns are included in the following summary statement. Vibration monitoring is necessary for the detection of fracture modes (significant crack propagation can occur with minimal release of debris); wear monitoring techniques are the best choice for detection of gross pitting, spalling, or gross scuffing defects; and oil analysis techniques provide the only means of detecting small build debris, micropitting, fretting, and the early stages of pitting and scuffing (although monitor filters could conceivably replace oil analysis in the future); and optical inspection aids are necessary for the detection of internal corrosion, and aiding the identification and extent of damage flagged up by other systems.

3.2. Vibration Monitoring

Whilst the components which may exhibit pitting or fracture modes are rotating, it would be impractical to attach sensors to rotating members. The method is therefore dependent upon the defect influencing the dynamic characteristics of the casing. It must therefore be able to discriminate between signals from different components, cope with signal attenuation at interfaces, and with variability in response from one casing to another, and between sensing points. Experience of monitoring gear defects arising in overload rig tests has demonstrated that by suitable choice of sensors, fixing arrangement, signal conditioning, sampling, and analysis techniques, these requirements can be satisfied. Furthermore, experience to date on Westland 30 aircraft has shown that miniature accelerometers with microdot connectors and PTFE insulated low noise coaxial cable survives the relatively hostile environment of a helicopter gearbox, and the frequent accessing activity associated with flight development. 'Gorilla-proof' versions of such accelerometers are available, but not without penalties on cost, installation requirements, and frequency response range.

A major potential problem for remote vibration monitoring is that of load sharing introduced by the gear arrangement. The simplest system presents no problem - a single load path configuration such as single spiral bevel gear pairs in tail rotor and intermediate gearboxes. A defective tooth will be subject to full load at some point during the mesh cycle. In mutli-mesh configurations such as epicyclic gears, the existence of several parallel load paths means that a defective tooth on a planet gear will be off-loaded by the other planets, and system excitation will be much less than that due to a defect of similar magnitude in a single mesh situation. This has proved a major factor in disqualifying simple vibration levels/analysis techniques for fault detection in helicopter gearboxes. An attempt has been made to indicate in fig.1 the influence of defect severity and of load path configuration on the sophistication of analysis necessary. For this purpose load path complexity has been classfied thus :-

a - single load path (single mesh)
b - two parallel load paths
c - more than two parallel load paths

The degree of sophistication of vibration analysis has been classified thus :-

1 - Raw time histories/Raster display
2 - Averaged time histories/frequency spectra
3 - Enhancement of signal averages
4 - Dynamic load index
5 - Enveloping techniques

Experience from overload rig tests to date (see fig.1) indicates that the simple techniques can be used for cases of severe erosion of profiles of <u>all</u> teeth, but for individual tooth damage/fracture signal averaging techniques are necessary - for multiple load paths or less significant defects enhanced signal average techniques are necessary.

To satisfy the requirement of minimum maintenance workload and skill levels in implementing the technique, the analysis facilities must be simple to operate and be capable of producing automated results against clearly defined rejection criteria. Reliance upon visual examination of waveforms or frequency spectra would not be acceptable in any but exceptional circumstances. The damage propagation rate for defects serious enough to influence dynamic characteristics is such that ground based analysis should be performed at frequent intervals, or preferably the analysis should be amenable to on-board processing with indications to the pilot.

3.3. Wear Debris Monitoring

Required for monitoring surface wear in gears and bearings - for which damage progression rates are very much longer than fracture modes - wear monitoring systems should provide indications to maintenance personnel rather than to the pilot. The requirement to minimise maintenance work load and specialist skills means that an automatic counting system is preferred to simple magnetic plugs. A remote indicating system must be able to distinguish between inoffensive small wear or build debris on the one hand, and significant wear particles on the other - a threshold in the region of 0.2 mgms appears significant for moderate pitting of steel gears and spalling of bearings. Whilst non-metallic debris is of concern from the point of view of seal wear or oil jet blockage, unless the problems can be corrected without stripping the gearbox, it is sufficient to monitor wear of the high strength steel components (seal wear can be monitored independently by noting oil consumption/ observing leakage; wear of bronze or silver plated cages will influence dynamic characteristics before rejection is necessary). The main problem for wear sensors is that of having adequate catch efficiency - large particles 'wetting out' before reaching the sensor, or sensors only 'seeing' a fraction of the total scavenge oil flow. Oil filter inspections, of course, overcome this problem, and are not restricted to ferrous particles, but apart from the extreme case of filter blockage which is already covered by pressure drop measurement, filter removal and inspection can impose a significant maintenance penalty.

3.4. Oil Analysis

The problems for on-line oil analysis are such that solutions to date have proved to be either ineffective, heavy, or costly. As discussed in relation to fig.1, oil analysis techniques are required only for detecting defects in their earliest stages of development.

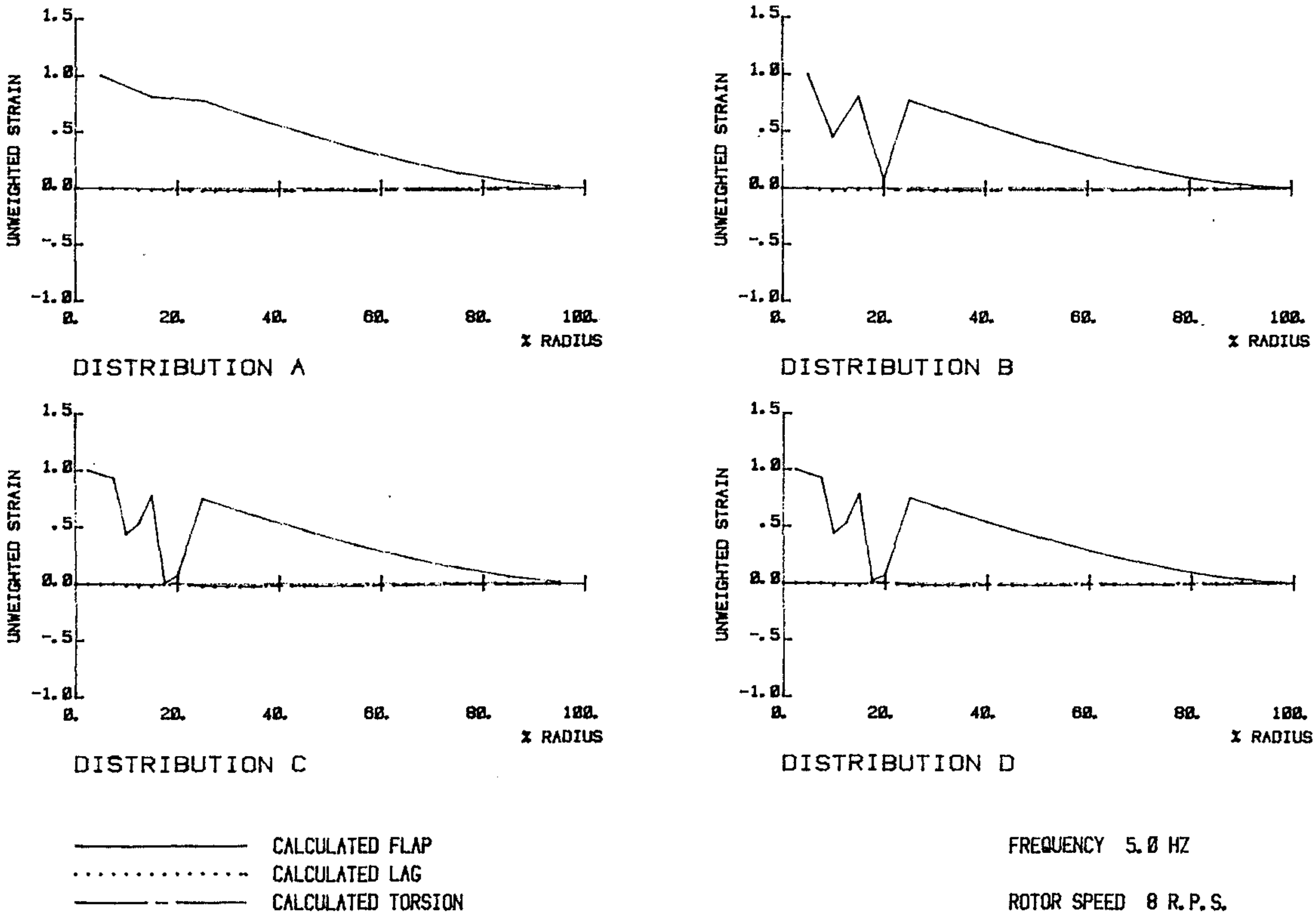


Fig 18 Calibration Mode 1 Fundamental Flap Strain patterns

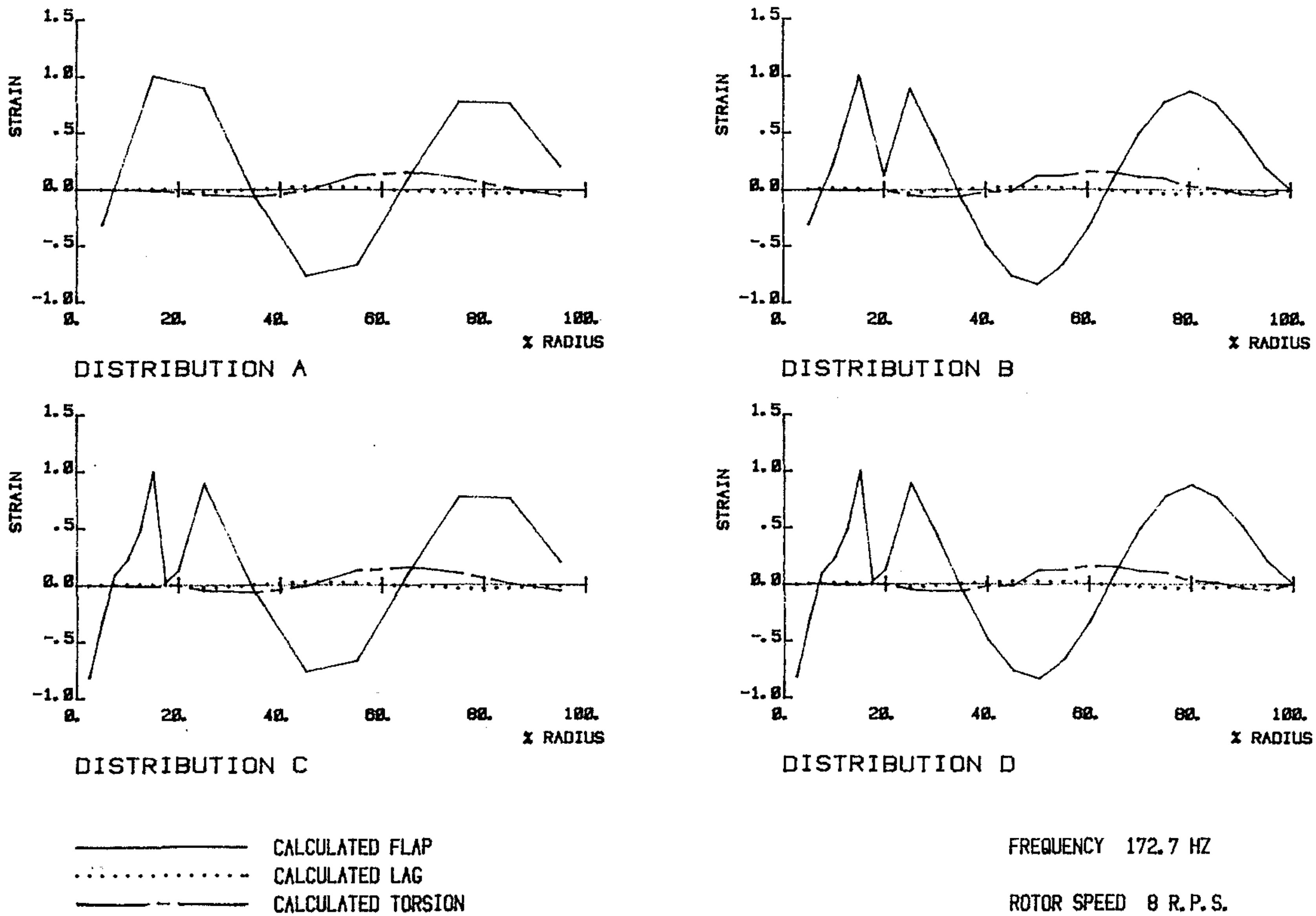


Fig 17 Strain patterns of Mode 7

They therefore have an important part to pay in transmission development activity for early identification of defects for which design modification is necessary. Also damage progression rates may be such that the slow response of laboratory based analysis facilities can be acceptable for service aircraft. However, three seemingly fundamental problems remain :-

a) Significant variations in trends occur due to variability of oil transport efficiency and sampling procedures, as well as variations in debris generated at source for modes in early stages of development.

b) High maintenance workload, equipment cost, and slow response time.

c) The possible difficulties created by adoption of fine filtration demonstrated to be so effective in extending gearbox life (ref.2).

3.5. Borescope Inspections

The fundamental problem with intrascope inspection of internal components as a routine inspection method is the very large maintenance workload involved in close inspection of all working surfaces and critical areas of so many components. Also, serious cracks are often difficult to detect by optical inspection - even of clean, dry components on the bench. There may well be occasions however, when establishing confidence in the other HM techniques during initial life extension, that borderline indications justify in-situ inspections with borescopes. Similarly with 'known problems' or 'batch problems', visual inspection of limited areas on a limited number of gearboxes would be acceptable. Similar considerations apply to other NDT techniques such as portable dye-penetrant, eddy current and ultrasonic checks which have been used, but apart from casings are limited in application by component accessibility.

4. THE SOLUTIONS

Significant progress has been made within the last two or three years in developing health monitoring systems to satisfy the above requirement and to overcome the problems outlined. The systems described are currently being applied to the Westland 30 transmission in service, and further developments are in hand for growth versions of W.30, Lynx, and for EH101.

4.1. Vibration Monitoring of Gears

The permanent installation comprises six Birchall A23/SI miniature accelerometers mounted on the top cover of the main rotor gearbox, one on each of the tail rotor and intermediate gearboxes; two azimuth markers - the existing one used for blade tracking on the main rotor shaft, and an additional one on the tail rotor drive shaft; and cables routed to a common sampling connector in the cabin. A portable recording unit comprises a Teac 14 channel recorder, and Birchall charger amplifiers. Recordings are made during a short ground run at predetermined single and twin engine conditions. Analysis is performed on a Digital PDP 11-34 computer having a Micro Consultants ADC, Prosig acquisition software packages, and Kemo 16 channel programmable filter. Data sampling rate is 100 K samples/second (one data channel plus azimuth). The WHL analysis programmes are standardised, and prompted operation via a VDU interface is very straightforward. The results of data integrity checks and preliminary signal averaging are presented immediately on the VDU in terms of numerical parameters. Enhanced signal averages are then computed, in which certain dominating but unresponsive harmonic components are deleted from the data. The result is a waveform containing the higher harmonics of each individual tooth, in which the transmission error characteristics, plus any individual defects such as root cracking or significant pitting of the working flank can be clearly seen. An example of the power of enhanced signal averaging can be seen in comparing fig.3 with straight signal averaging in fig.2. Both relate to a tooth root fracture in a triple load path situation from an overload test to failure. Whilst visual examination of such waveforms provides a quick appraisal of gear condition, it is not necessary - choice of a suitable statistical parameter which can reflect a change in the characteristics of one or of several teeth permits an automated numerical assessment of gear condition against predetermined rejection criteria - whether expressed in terms of absolute levels or trends (slopes). Application to a number of gear failures produced in overload rig tests has demonstrated the usefulness of the normalised sixth moment of the enhanced signal averaged data, referred to as M6*, where

$$M6^* = \frac{1}{(N-1)\sigma^6} \cdot \sum_{i=1}^{N} (x_i - \bar{x})^6 \qquad \text{(standard notation)}$$

Fig.4 shows a trend plot covering an incident of gross pitting, and Fig.5 a typical trend plot from aircraft data.

Portable equipment capable of acquiring and analysing vibration data in this way has been produced by Stewart Hughes Ltd. of Southampton. They have developed a wide range of diagnostic packages for gears and bearings, many of which would be appropriate to gearboxes built to lower standards than those in helicopters.

On-board processing facilities are under consideration for later versions of Westland 30, Lynx, and EH101.

4.2. Wear Debris Monitoring

A remote indicating system capable of quantifying either the amount of wear debris or numbers of particles above a threshold size is clearly necessary to satisfy the requirements outlined earlier. Research effort at WHL resulted in an inductive sensor capable of satisfying this need, but at the same time TEDECO in the USA produced their Quantitative Debris Monitoring System, also using an inductive sensor, and a signal conditioning unit which counts 'large and 'small' particles. WHL cooperated in this development, particularly in respect of setting threshold levels, and signal amplification to overcome EMC problems. A production version is fitted to the Westland 30, with a sensor in the sump of the main rotor gearbox positioned to give best catch efficienty as established during development rig tests. The signal conditioning unit with output indicators is situated in an avionics bay where it is readily accessible for regular reading. The system is shown in fig.6 together with a plot of output data relating to an arising which occurred during development. The oil filter was the only other 'system' to detect this arising.

Simple magnetic plugs are also fitted to all Westland 30 gearboxes, considerable experience have been accummulated with them by military and civil operators in the UK.

On later versions of Westland 30, Lynx, and on EH101 it is envisaged that all gearboxes will be fitted with the QDM system, and that outputs will be fed into a centralised processing system together with vibration data, oil system parameters, etc. Evaluation of full flow mounting arrangements will also be made in pursuit of maximum catch efficiency.

4.3. Oil Analysis

Oil samples are taken regularly from all Westland 30 gearboxes, subjected to spectrographic analysis. Ferrography is also applied, and an electron beam microscope with EDAX probe is also available for identification of source material and hence component type. WHL back-up is being provided in this area because of the long experience and reliance in these techniques by UK military and civil operators.

Fine filtration is under consideration for future versions of Westland 30, Lynx, and for EH101, and it is not yet clear whether this will make oil analysis methods impossible, or whether the cleaner background will enable the often irregular response of oil analysis systems to be improved, albeit at a lower level of ppm.

Simple monitor filters are considered to be a desirable addition to the main oil filter, in any event.

4.4. Borescopes

Regular borescope inspections are not advocated, but provisions have been made in Westland 30 gearboxes to permit in-situ visual inspection of all the main gears and some other components, for doubtful/emergency situations. The provisions include borescope ports and guide tubes to enable commercially available flexible borescopes to be used.

5. CONCLUSIONS

The requirements and difficulties are such that no single health monitoring technique is adequate for helicopter gearboxes. It is considered that the ideal ingredients are :-

1. Vibration monitoring for rare but potentially catastrophic fracture modes in gears.

2. Remote wear debris monitoring of the TEDECO QDM type for all common wear modes in gears and bearings.

3. Oil pressure and temperature, or flow, for oil system problems.

The Westland 30 transmission is provided with these systems together with the traditional oil sampling facilities, magnetic plugs, inspectable filters, and with provisions for borescopes.

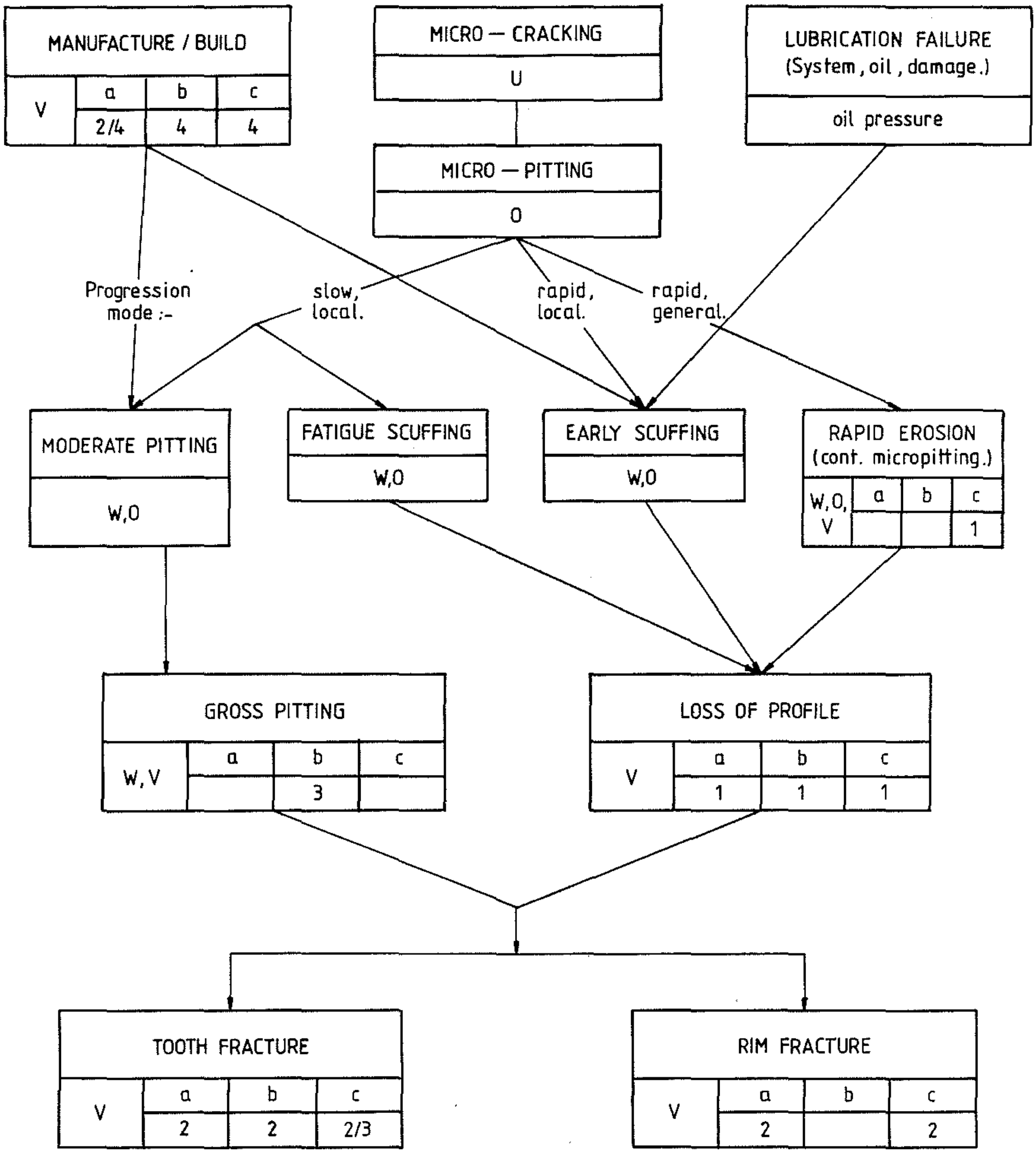
6. REFERENCES

1. B.A. Shotter, Scuffing and Pitting - recent observations modify traditional concepts, IFTOMM - JuDEKO World Symposium on Gears, Dubrovnik, Sept. 1978, paper B-26.

2. W.A. Hudgins, Oil Debris Discrimination and Filtration System, Interim Report, Applied Technology Laboratory, US Army Research and Technology Laboratories (AVRADCOM) Fort Eustis VA, Feb.1981.

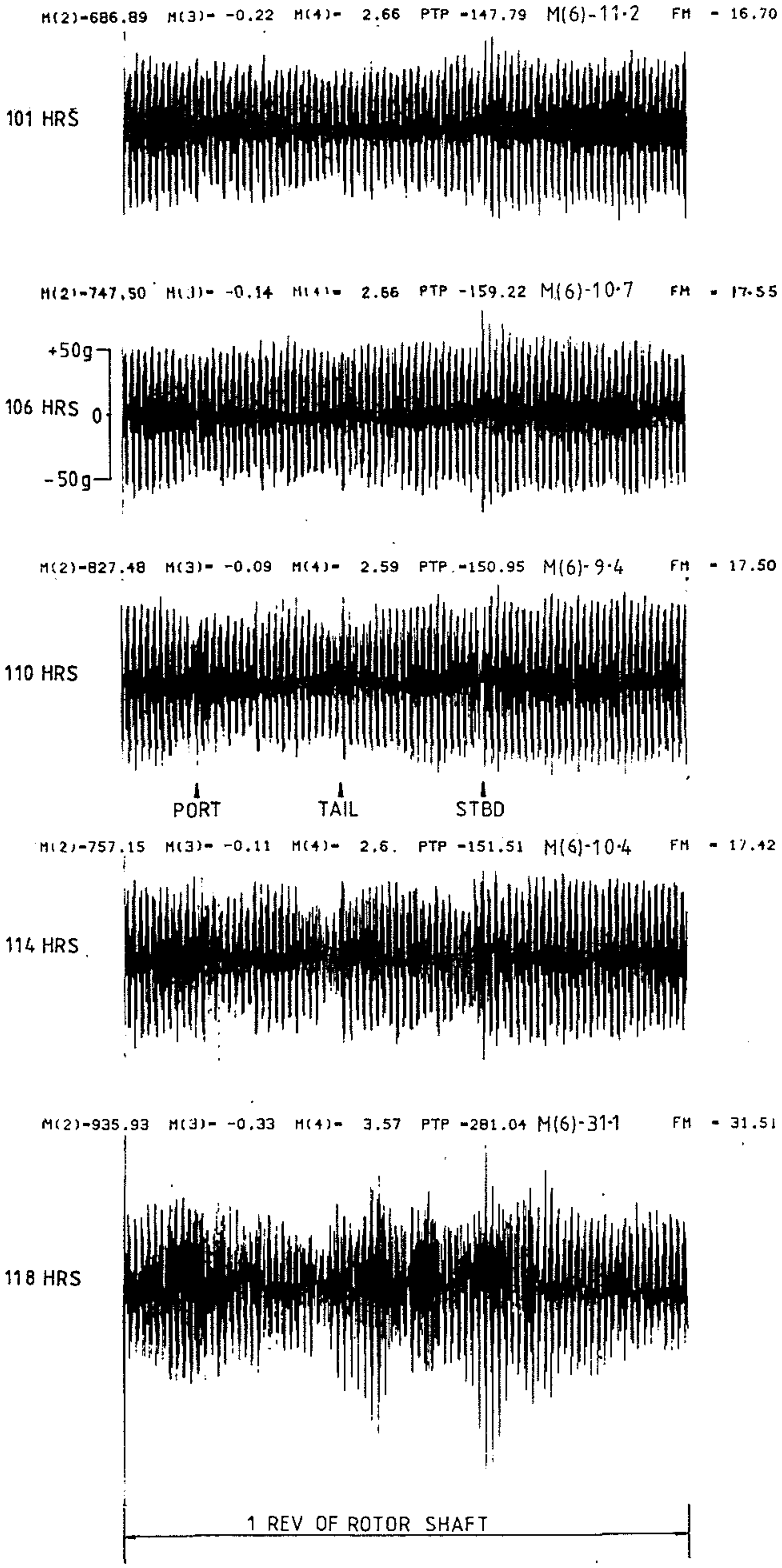
7. ACKNOWLEDGEMENTS

The author acknowledges the original work of Mr. M.J. Stuckey, and Dr. M.L.W. Salzer relating to WHL vibration analysis systems, and to several other members of the Mechanical Research Department for their assistance - Messrs. Head, Berners, Kench, Little, and Cameron.



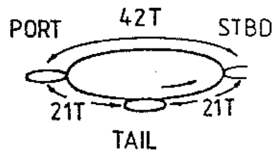
KEY :- U - undetectable
O - oil analysis method
W - wear debris monitoring
V - vibration analysis
refer to section 3.2 of text for key to numbers and small case letters.

FIGURE. 1. Failure development patterns in helicopter gears, and current status of detection techniques.



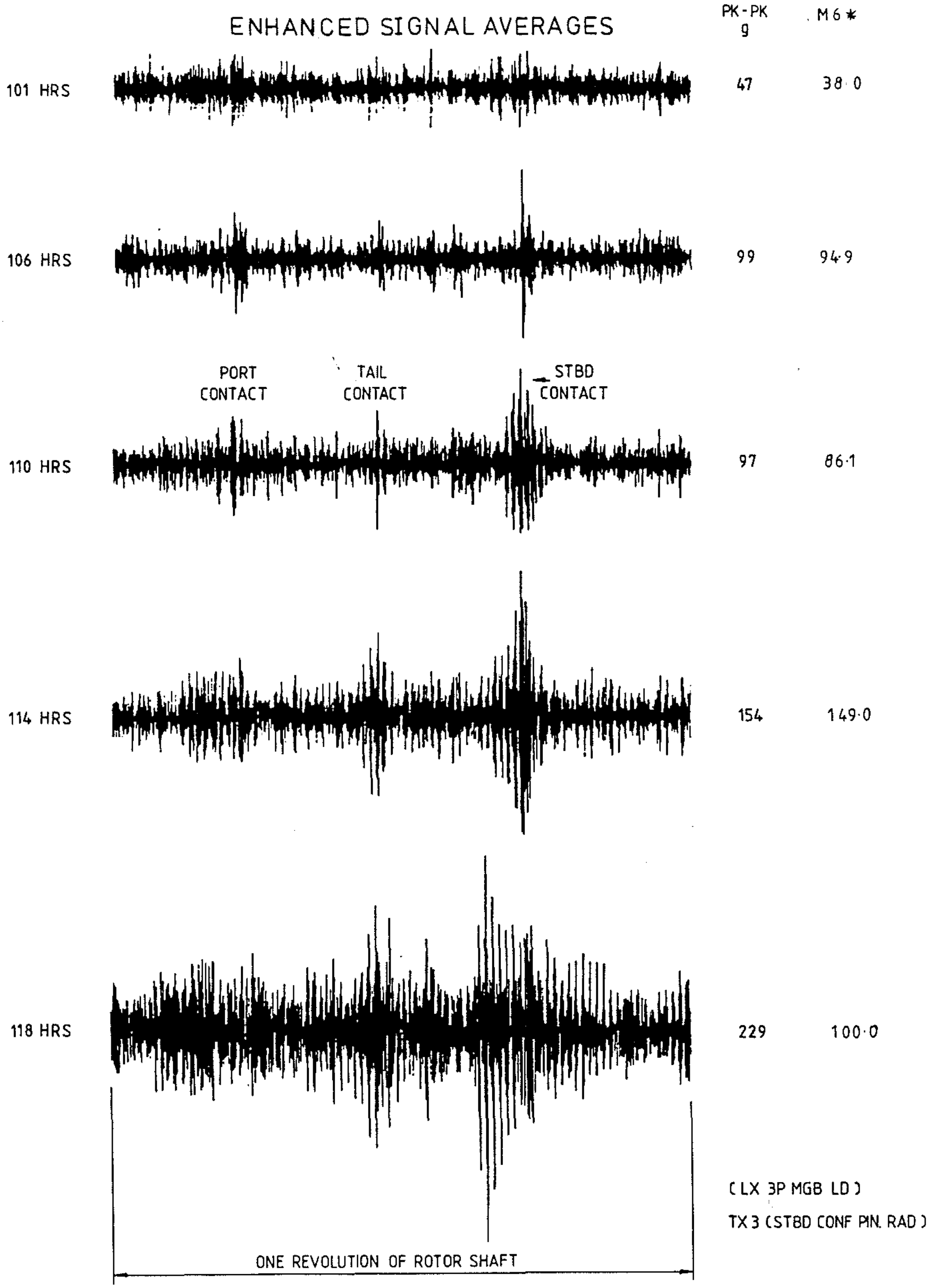
NOM. TORQUE
1143 / 1143 /(120 TTO)
LBF FT

TRANSDUCER 3
(STBD. CONF. PINION
RADIAL)



BENDING FATIGUE FAILURE OF
CONFORMAL WHEEL —
LYNX 3P MGB (REF. LD)
AVERAGED TIME HISTORIES

FIGURE-2



BENDING FATIGUE FAILURE OF CONFORMAL WHEEL

FIGURE:-3

Fig 4a Gross pitting

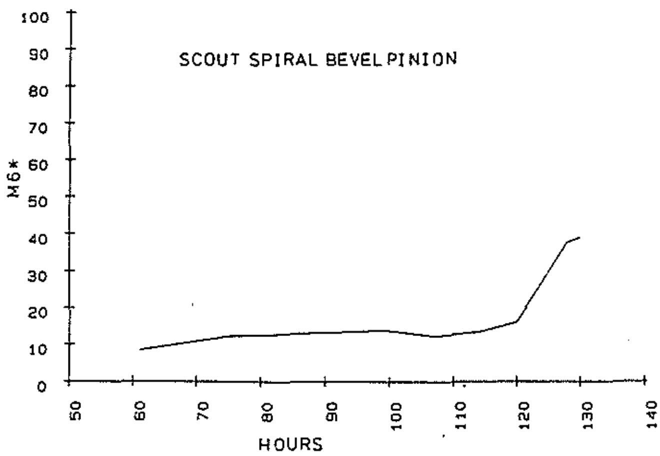


Fig 4b Scout Spiral Bevel pinion

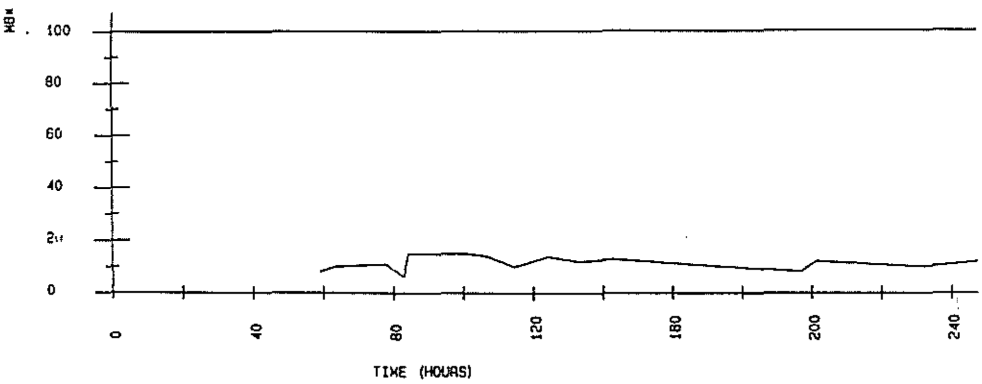


Fig. 5. Westland 30 Development Aircraft Trend plot of enhanced signal average

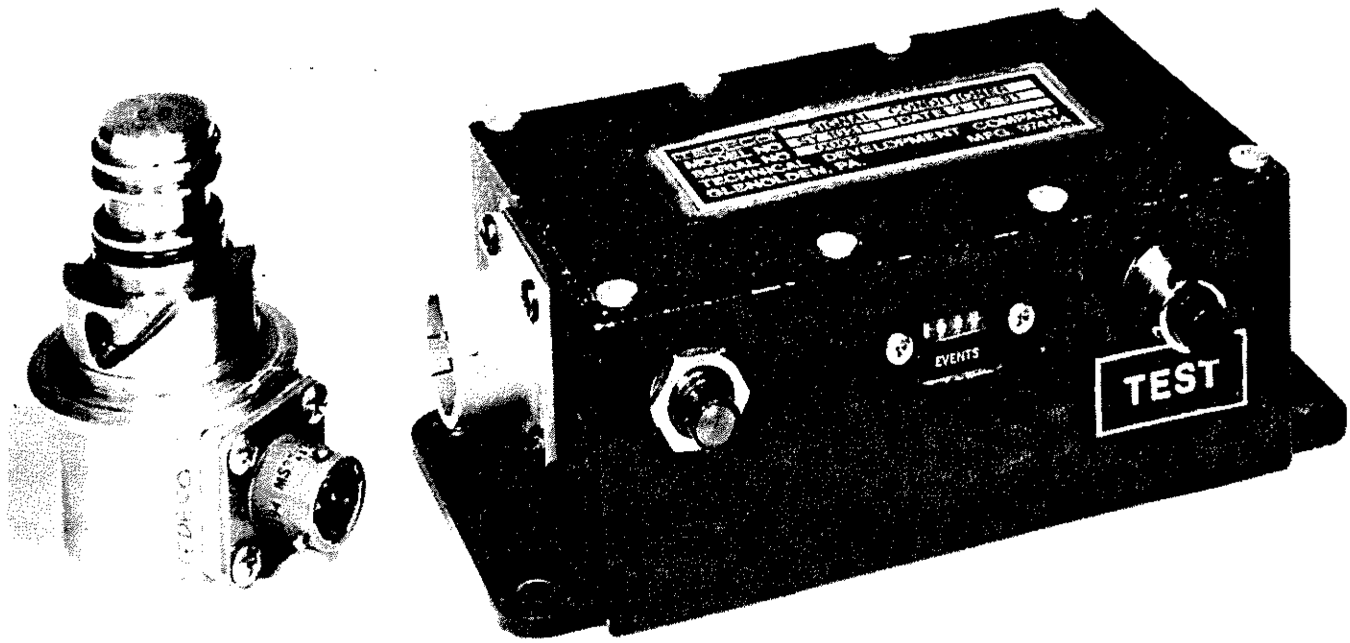


Fig 6a TEDECO Quantative Debris Monitor

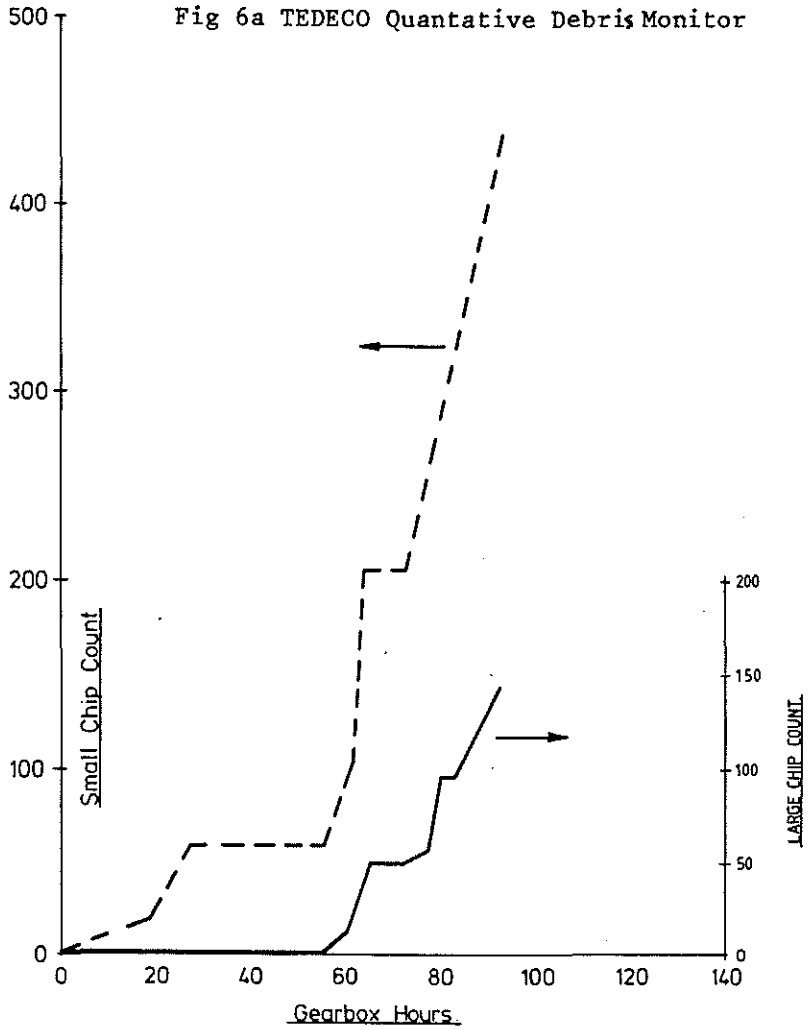


Fig 6b Q.D.M. Wear Sensor in Westland 30
Main Rotor Gearbox-Fretting Incident