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OPERATIONAL EXPERIENCE WITH THE ADVANCED TRANSMISSION HEALTH MONITORING TECHNIQUES ON THE WESTLAND 30 HELICOPTER

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Operational Experience with the Advanced Transmission Health Monitoring Techniques on the Westland 30 Helicopter.

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Abstract

The life extension programme for the Westland 30 Series 100 transmission is supported by an advanced package of health monitoring techniques, some of which are unique to this helicopter, in order to enhance the large increases in TBO periods to keep pace with the high flying rates of the civil operator. The objectives are to maximise airworthiness and to offer economic benefits in terms of accelerated growth in time between overhaul and hence eventually to on condition status for removal. This paper reviews experience with these health monitoring techniques both in commercial operations and in development aircraft programmes, demonstrating effectiveness of the system with actual case histories. The paper reflects the encouraging increase in operator commitment providing evidence that detection of faults can be achieved by such a comprehensive package of health monitoring techniques. The paper also highlights future systems to further enhance the efficiency of health monitoring.

1. Introduction

Prior to the entry into service of the Westland 30 civil aircraft the general procedure for life extension of military aircraft transmissions was by sampling three of four units at intervals of 200/300 hours from the initial release life of, in the majority of cases, 300 hours. As the flying rate of the military aircraft user was in the order of 250/300 hours per year this method of extending the transmission lives was compatible with requirements. However, this was time consuming and incurred recondition costs for the user, when in most instances the gearboxes would have achieved many more hours of flying.

The Westland 30 aircraft however was designed for commercial operation with expected flying rates 100/150 hours per month and possibly more on some occasions.

Westland experience of aircraft flying at such high usage rates was very limited and therefore a different approach to the life extension programme was needed.

The proposed concept used for the Westland 30 aircraft life extension programme to create a rapid increase in the scheduled removal times, whilst maintaining the required safety standards was by on condition removals and sampling at suitable intervals on a small number of transmission sets. The programme sought to increase T.B.O. lives by 500/1000 hour intervals, supported by the traditional techniques of magnetic plug examination and oil analysis together with diagnostic filter examination, oil pressures and temperatures augmented by the relatively new health monitoring techniques. These non-mandatory health monitoring techniques used were:

(i) Spectrometric oil analysis - S.O.A.
(ii) Ferrographic oil analysis - F.A.
(iii) Quantitative Debris Monitor - Q.D.M.
(iv) Introscope inspections.
(v) Vibration Monitoring System - V.M.S.

2. Brief Discussion of Health Monitoring Techniques Used

2.1. Oil Analysis

Spectrometric oil analysis, widely used for a number of years, has been found to be of limited value in UK military experience, although it is occasionally relied upon to monitor specific known problems characterised by the production of very small size debris (5 microns max). In UK operation of Westland 30 it has provided a valuable means of early indication of wear, mainly due to operator participation in the regular sample taking within the required time period after shutdown, which has allowed, in the majority of instances, firm trends to be established for the elements analysed. Militating against S.O.A. in general are the time delay in return of sample and analysis, variability in results due to variations in oil sampling and in analysis where several different laboratories or equipments are employed. Problems can and have arisen when contract analysis laboratories quote different warning levels to those promulgated by the helicopter manufacturer, and when time limits between shutdown and sample taking are exceeded.

Ferrographic oil analysis equipment comprises two versions, both of which deposit principally ferrous debris in a size-graded manner. The direct reading version, used for the W30, automatically assesses the amount of debris collected at the large and small extremes. The analytical version deposits the oil-borne debris onto a glass slide suitable for optical examination. In general the readings obtained from the Direct Reading version tend to be erratic and form no firm trend that could be used for gearbox removal as a single system without corroboration from other techniques. The Analytical Ferrograph facilitates an understanding of the nature of the problem, but the process is too slow to be of use in determining quantitative trends.

2.2. Magnetic Plug Examination

Magnetic plugs have long been used for trend analysis by transferring the debris to transparent tape and mounting it on a record card in a time sequence. This requires time, effort and office or laboratory space and skilled judgement in differentiating between a heavy deposit of small innocuous debris and significant wear particles. This problem tends to be worse during the first 50 hours or so after installation of new or overhauled gearbox when build debris or running-in wear particles can suddenly be released as a slug from a pocket in the casing or oil-way due to a particular sequence of aircraft attitude changes or due to the flow induced release of a damming particle or semi-adhered burr.

2.3. TEDECO Quantitative Debris Monitor

The Q.D.M. system marks a step improvement in wear debris monitoring technology, satisfying almost all of the requirements identified by Westland. The inductive sensor produces a small voltage spike proportional to the mass of ferrous debris arriving at the sensor. The amplified output is fed to a signal conditioning box which contains two comparator circuits and displays the number of counts above each of these two threshold levels. The sensing response time is relatively fast so that individual wear particles above the threshold mass levels are counted. The system was incorporated in the main rotor gearbox of the Westland 30 helicopter during development (designing the sensor to fit an existing blanked hole in the sump) and is standard fit on the production helicopter. The display unit is housed in the starboard avionics bay, the chip counts being recorded on a daily schedule. The small and large chip thresholds which currently correspond to approximately .2 mgms and 1 mgm give the capability to track wear modes of both types - those which continue to generate debris at virtually constant small size and those which produce larger particles as damage progresses.

A more detailed description of the Q.D.M. system and vibration analysis techniques is given in reference 1.

2.4. Vibration Monitoring System

Vibration analysis is applied to the gears in all Westland 30 gearboxes using permanently mounted miniature accelerometers on gearbox casings, azimuth marker and cables meeting at a common connector near the cabin door. Vibration data recordings are taken during a short ground run at predetermined single and twin engine conditions at approximately 100 hour intervals. Signals are recorded from the accelerometers into a Teac 14 channel recorder and Birchall charge amplifiers. The analysis is currently performed on the vibration health monitoring computer at WHL Yeovil using software developed by Westland. The results of the data integrity checks and preliminary signal averaging are presented immediately on a 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 flank can be clearly seen. Irregularities in this wave form are characterised by a numerical statistical parameter, M6* (ref. 1).

2.5. Insitu Inspection

Provisions for borescope inspection of Westland 30 gearboxes have been made primarily to aid gear tooth meshing pattern assessment following no-load testing which has recently been introduced. The provisions include a flexible borescope and light source and a set of guide tubes which are inserted in normally blanked ports in the casing and direct the borescope to each gear mesh. These facilities can be used to confirm wear problems indicated by the wear monitoring systems without removing the gearbox from the aircraft and can be carried out in the open, for example on an oil rig or downtown helipad.

3. Transmission Health Monitoring Procedure

3.1. Sampling

To enable the operator to benefit from less frequent removal of the transmission by health monitoring support instead of life assessment it was made the operators responsibility to acquire the data from the respective health monitoring systems at the correct time intervals in accordance with the maintenance manuals. Initially it took time and public relations effort to obtain full co-operation of the operators to comply with maintenance manual and service bulletin requirements.

Operators can react immediately to magnetic plug and Q.D.M. readings, according to instructions in the maintenance manual. These results are returned to WHL as soon as possible for comparison with the data base relating to all service helicopters.

3.2. Analysis of Data returned to WHL

In addition to operator decisions aided by the maintenance manual, further overall assessment of the health monitoring indication is made by a transmission specialist at WHL.

Analysis of data is completed within one day of receipt and the results returned to the operator's engineering authority within a week as a summary report, which highlights any potential problem areas, analysis of results and actions to be taken. Problem areas which affect the removal of a gearbox are covered by a direct phone contact with the operator's station engineer.

Oil analysis trends from all the gearboxes are compared and can be presented as a single trend or up to ten aircraft gearboxes for overall trends. Seven elements are monitored from the main gearbox, three from the intermediate gearbox and four from the tail gearbox. Iron is usually the predominant element for an indication that more than normal wear is taking place inside the gearbox and figure 1 shows the trend pattern for iron from the main gearbox described in 4.1. compared with the trend patterns in healthy gearboxes.

Q.D.M. readings are recorded daily and any rise of 3 or more in 15 hours of flying requires the gearbox to be removed. Built into the system is a press to test facility which the operator is required to operate after every 100 hours of flying to ensure correct functioning.

The M6* value derived from the vibration analysis for each gear is presented in tabulated form for recording purposes for each aircraft. Figure 4 shows the distribution of M6* results from service and development aircraft (1643 values obtained from 106 different gearboxes on 17 aircraft).

Two points are above the rejection limit of 100, one relates to modest pitting that occurred in a development tie down test (para. 4.5.), and the highest relates to a partial tooth fracture (para 4.3). Three points are in the cautionary region (M6* = 50 to 100), the remainder are all below the caution level indicating the stability of the M6* parameter for non-defective gears.

3.3. Storage of Data

Dedicated software has been developed to analyse, store and reproduce data from all gearboxes in service so that trends in addition to threshold limits can be monitored, and gearbox replacements planned.

4. Case Histories

Since the first aircraft entered service in April 1982 approximately 15,000 flying hours have been completed by aircraft at British Airways Helicopters (North Sea Operations), Omniflight (Pan Am service in New York), Heli-Hire (charter) and the now ceased Airspur operator. Fortunately there have been few occasions when gearboxes have been removed due to one or more of the health monitoring systems indicating an impending failure. The gearboxes that have been removed are briefly described as follows:-

4.1. Case History No. 1 Main Rotor Gearbox

After approximately 200 hours of flying it could be seen from S.O.A. results that this gearbox was generating a rising trend of iron particles in the oil, which was clearly different from the trends of the other gearboxes in service as depicted in Figure 1. This trend continued until the gearbox had achieved 837 hours at which stage the level of particles in the oil was approaching the permitted limit. At this stage the Ferrographic Analysis indicated an increase in the larger particle size.

However at the 826 hour stage the Q.D.M. indicated a rise and by 837 hours had risen four counts on the large chip counter and on this evidence the gearbox was removed from the aircraft, reference figure 2. Subsequent stripping revealed modest pitting of the output gears.

This case shows the sensitive detection powers of the Q.D.M. monitoring system in supporting the removal of a gearbox well in advance of potentially catastrophic failure.

Examination of the vibration enhanced signal average did show some abnormalities but did not affect the M6* value significantly. It is felt that any further growth of the pitting might have affected the gear meshing dynamics sufficiently to be detected in the vibration analysis as was previously found during development aircraft flying activities, where higher than normal flight loads were used.

This particular defect was not of a severe nature and the gearbox would have been expected to have achieved at least a 1000 hours flying when the routine introscope inspection would have found the pitting and the gearbox rejected. Modification action to alter the tooth lead and edge radius in the affected area has proved successful in eliminating the pitting.

4.2. Case History No. 2 Main Rotor Gearbox

Unfortunately not all operators committed themselves fully at the outset to use the health monitoring provisions. The first oil sample from this gearbox was taken at 626 hours and revealed an iron count of 161 ppm - well above the allowable 50 ppm and if it had been known by WHL the gearbox would have been removed immediately. However the operator allowed the gearbox to continue in service without investigation. At 976 hours the iron content reached 230 ppm. The operator then changed the oil and 50 hours later the iron content had dropped to 67 ppm - still outside the permissible limit. The gearbox by this time had achieved 972 hours and was removed for a 1000 hours overhaul. Subsequent examination revealed surface pitting of all teeth of the port input pinion and bevel wheel, which was determined to be the result of an isolated case of incorrect tooth meshing pattern. Current research activities into build assessment of gear meshing patterns via vibration health monitoring is aimed at eliminating this possibility.

The wear sensor readings were not recorded by the operator during this time and no results of magnetic plug examinations were received.

Vibration data was recorded at spasmodic intervals during the life of the gearbox but the vital data was missing due to failure of the operator to follow defined procedures.

4.3. Case History No.3 Main Rotor Gearbox

This gearbox was removed due to a rising trend in the Q.D.M. count, at 232 hours. Rumbling noises and vibration had been reported by the pilot at 216 hours at which time a vibration recording was taken. The plug examination and oil analysis did not reveal any problem areas up to and including the 193 hour stage. Subsequent stripping of the gearbox revealed one tooth to be missing from an output stage pinion. Analysis of the vibration tape, although after the event, did show the tooth failure. Figure 5 shows the enhanced signal averages obtained from the only two recordings from this gearbox.

From Figure 3 it can clearly be seen that if rejection limits promulgated for the wear sensor had been observed the gearbox would have been removed well before the pilot had sensed vibration.

Further examination of the pinion failure revealed a large non-metallic inclusion in the material which caused the tooth breakage.

4.4. Case History No.4 Main Rotor Gearbox

The first ground run on G-BGHF (tied-down test with the aircraft operating at high power levels) resulted in creep of the liner and bearing raceway at the lower end of the output hub, producing fine debris for a period of 56 hours running. It was decided to continue running with frequent monitoring inspections because the liner spinning had no significant influence on the functioning of the gearbox, and a design modification was being satisfactorily evaluated in parallel rig test. The only monitoring techniques which produced a definitely increasing trend during this period were S.O.A. and the QDM total chip count which responded from the start of the test, reference figure 6. With continued running the QDM large chip count also responded, some debris was collected by the magnetic plug, followed by the oil filter blockage indicator. Had this been a service aircraft, the gearbox would have been rejected at the 57 hour point when the QDM large chip count exceeded 4. However, the development test was continued to 145 hours during which time, the filter clogged several times.

During this period there were no indications of dynamic abnormalities from vibration analysis, and the oil analysis techniques, spectrographic analysis and DR Ferrography produced zero and decreasing trends respectively. Some debris was collected by the magnetic plug, but the QDM and filter blockage indicator were the only systems which followed the progression of damage, the 'plateaus' in the QDM response corresponding to filter element changes and start-ups (at ambient temperatures down to -10°C). The QDM indications were also confirmed by debris found on the probe, and by the bearing liner condition at strip, the larger debris resulting from trepanning and fracture of some of the bearing retention features.

4.5. Case History No.5 Main Rotor Gearbox

During tied-down aircraft certification testing of the transmission with Rolls-Royce GEM 60 engines fitted (W30 series 100-60) modest pitting occurred on some teeth of one of the pinions driving the output wheel. The increased power transmitted by the same gearbox resulted in slightly different deflection characteristics of the casing, necessitating slight modification of the end-relief on the pinion teeth. The QDM total chip count (small chips, since no large chips were counted) increased from 1680 airframe hours at a rate increasing to nearly three counts per hour until 1720 hours, after which it levelled out. From 1750 hours onwards, however, the vibration analysis results increased for this particular pinion and passed the rejection limit (M6* = 100) at 1815 hours, reference figure 7. The tied-down test was completed at 1870 hours and a borescope inspection confirmed slight tooth wear on the pinion identified by the vibration analysis. The tooth modifications referred to in para. 4.1. have demonstrated freedom from pitting in subsequent tests.

5. Discussion

5.1. Results from 15,000 hours service operation plus 2600 hours development aircraft operation has demonstrated that Quantitative Wear Debris monitoring, Enhanced vibration signal averaging, and Spectrometric oil analysis together form a very effective health monitoring package provided that the techniques are implemented and supported properly by manufacturer and operator. The optimum implementation is seen to be on-board processing, permitting immediate post-flight indications, with in-flight indications restricted strictly to those situations requiring modification of the flight. The on-board system under development for the W30-300 helicopter performs the M6* analysis and QDM trend analysis (ref. 2.).

5.2. Quantitative Debris Monitoring provides instant post-flight indication of fretting and pitting arisings and the one incident of tooth failure, where some break up of the fractured portion occurred. At present only the large chip (1 mgm) count is recorded on service aircraft, but both large and total chip count are recorded on development aircraft.

The rejection level, which is set at a very low accummulation rate, has been verified by experience and should not be ignored. Development experience indicates the value of monitoring total chip trends also for longer term planning of maintenance actions. Experience also validates the decision to avoid cockpit indications and rely upon post flight maintenance inspections. The preferred development path for QDM is to retain the dedicated maintenance display but also to interface with on-board maintenance processors (e.g. ref.2). The logic can be sufficiently well defined to replace manually logged counters with 'reject and caution' displays.

5.3. Vibration analysis (enhanced signal averaging) has provided clear rejection signals for gear tooth fractures and moderate tooth pitting. Tooth fracture, whilst a rare occurrence represents a potential hazard to airworthiness and justifies the best possible detection system. In deliberate tests to failure in gearbox rig tests, fractures have seldom released debris - vibration analysis has been the only method of detection, and has demonstrated greater sensitivity to cracks than visual inspection. Service experience with the technique has demonstrated the need to:

i) provide in-flight or immediate post-flight analysis.

ii) reduce operator involvement to the absolute minimum.

iii) revert to the transducers used on the original development aircraft.

The preferred solution to (i) and (ii) is the on-board processing system described in reference 2 currently under development. For aircraft for which this solution is inappropriate a ground-based dedicated analyser such as that currently being developed by Smiths Industries for the W30 series 100 helicopter (shown in figure 8) will become available.

5.4. Spectrometric oil analysis has provided an effective early warning for fretting wear and moderate pitting but requires operators and laboratories to closely follow the defined procedures. Experience with 3 micron absolute oil filters on a new transmission undergoing development at Westland tends to confirm the observation in the US Army Oil Debris Detection System trials (ODDS - ref. 3) that filtration of this level invalidated oil analysis techniques, although the few arisings may not have produced debris in the size range relevant to S.O.A.

5.5. The Civil Aviation Authority agreed extended TBO periods for the Westland 30 transmission conditional upon the use of the Health Monitoring Provisions.

5.6. There have been no false alarms. All the gearbox removals identified by the health monitoring system were fully justified during subsequent strip examination (Figure 9).

6. Future Systems

Further developments are planned for the Q.D.M. system and for at-the-aircraft vibration assessment.

For future growth versions of the Westland 30 helicopter the following is planned for Q.D.M. improvements:

(i) smaller sized sensors to suit tail rotor and angle gearboxes.

(ii) higher sensitivity to permit reduced small chip threshold.

(iii) Digital Data Processor with Light Emitting Diode displays to replace the counters.

The vibration monitoring system is to be improved by replacing the tape recorder with a portable analyser unit which will plug into the existing connector in the cabin during the short ground run and display the values of the enhanced signal average criteria for each gear in the transmission. This is currently undergoing bench tests (Figure 8).

On-board analysis is planned for the Westland 30 Series 300 helicopter to provide an indication of threshold exceedance immediately after each flight if necessary. This is part of a comprehensive package of health and usage monitoring functions for engines, transmission, rotor systems and hydraulics being developed in conjunction with Smiths Industries (Reference 2).

7. Conclusions

7.1. The health monitoring completed to date, although not given a 100% commitment at the initial stage by operators, has been effective in removing two gearboxes from aircraft prior to the defect becoming an airworthiness problem. The remaining two occurrences, if the operator had adhered to H.M. limits would have resulted in successful removal of the gearboxes and saved costly repair and recondition due to secondary damage.

7.2. The successful operation of the current health monitoring provisions depends on:

(i) Committment of operators to sampling procedures and declared rejection limits.

(ii) Rapid return and assessment of samples.

(iii) Communication with the operator on the results of analysed data and resulting actions.

7.3. The major advantages of the current health monitoring system are:-

(i) Eventual on condition status for the transmission which must be beneficial in economic terms for the operator in reduced operating costs and spares holding and reduced cost of repair and recondition assessment. A recent example has demonstrated that sufficient warning is given to permit planned gearbox replacement.

(ii) Improved airworthiness in early detection of possible defects which might become of such a nature as to affect the flight safety of the aircraft, and to reduce secondary damage.

7.4. The disadvantages of the current system implementation are:

(a) The elapsed time between removal and analysis of samples. This problem will be overcome for vibration analysis by use of the portable analyser and oil analysis may become redundant with the implementation of ultra fine filtration.

7.5. The effectiveness of the health monitoring techniques has lead to acceptance by the Civil Aviation Authority of significantly extended Time Between Overhaul for operators who commit themselves to the full health monitoring package. A Civil Aviation Authority draft paper has been produced defining health monitoring responsibilities of the constructor and operator.

References

1) D G Astridge - Health Monitoring of Helicopter Gearboxes, Paper presented at 8th European Rotorcraft Forum, Aix-en-Provence, France, September 1982.

2) D G Astridge and J D Roe - The Health and Usage Monitoring system of the Westland 30 Series 300 Helicopter Paper 81, Tenth European Rotorcraft Forum, The Hague, The Netherlands, August 1984.

3) W A Hudgins - Oil Debris Detection System (ODDS). Final Report USA AVSCOM TR-84-D-7, May 1984.

Fig. 1 Spectrometric Oil Analysis Results for Main Gearboxes

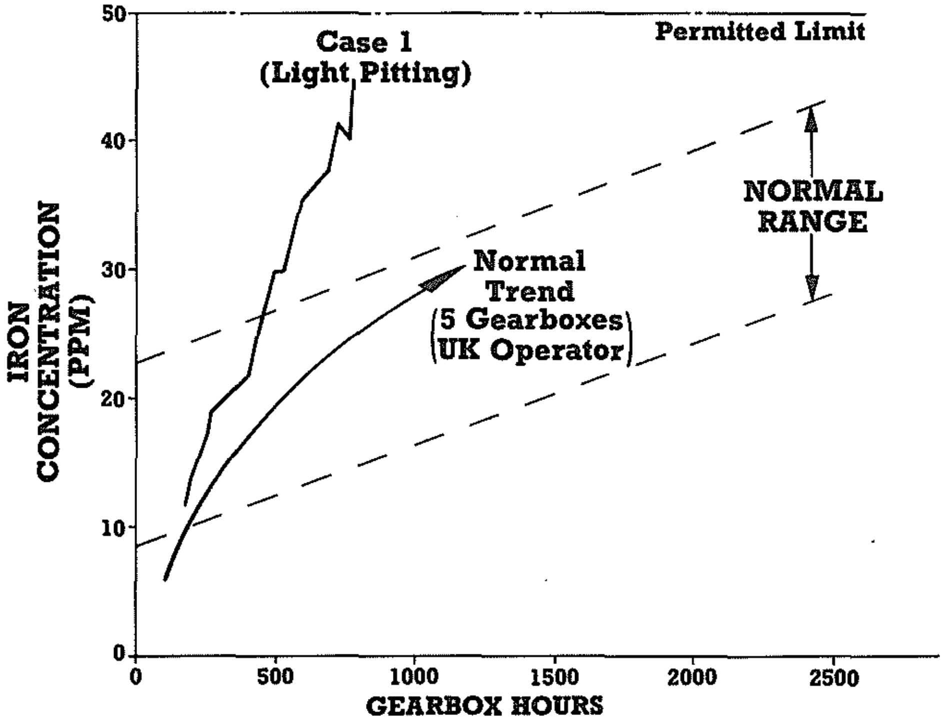

Fig. 2 Main Rotor Gearbox — Case History 1 (Light Pitting)

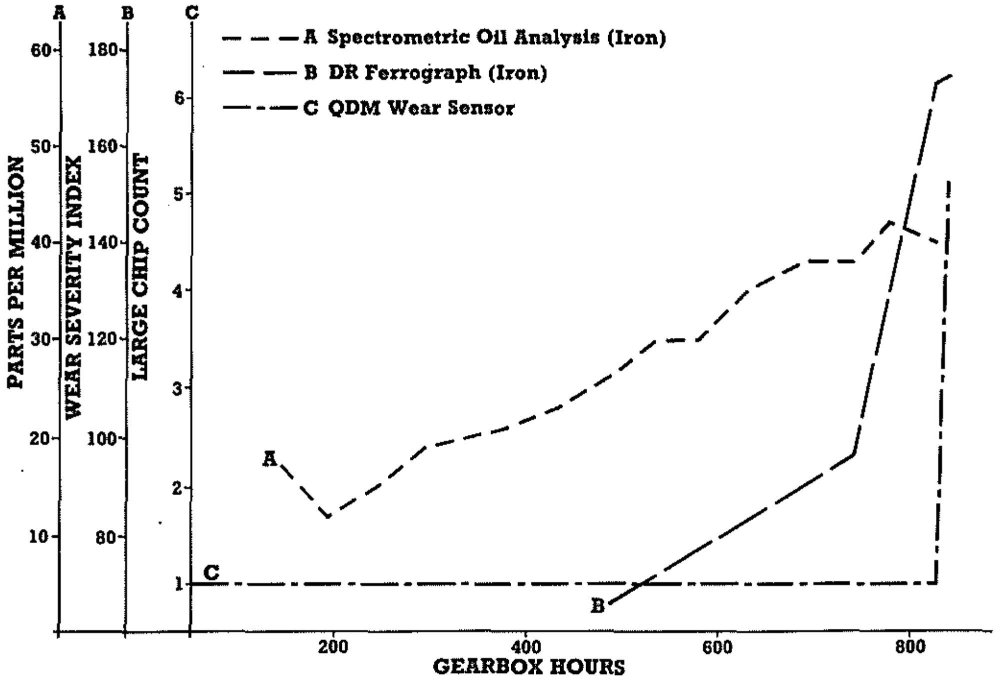

Fig. 3 Main Rotor Gearbox — Case History 3 (Tooth Fracture)

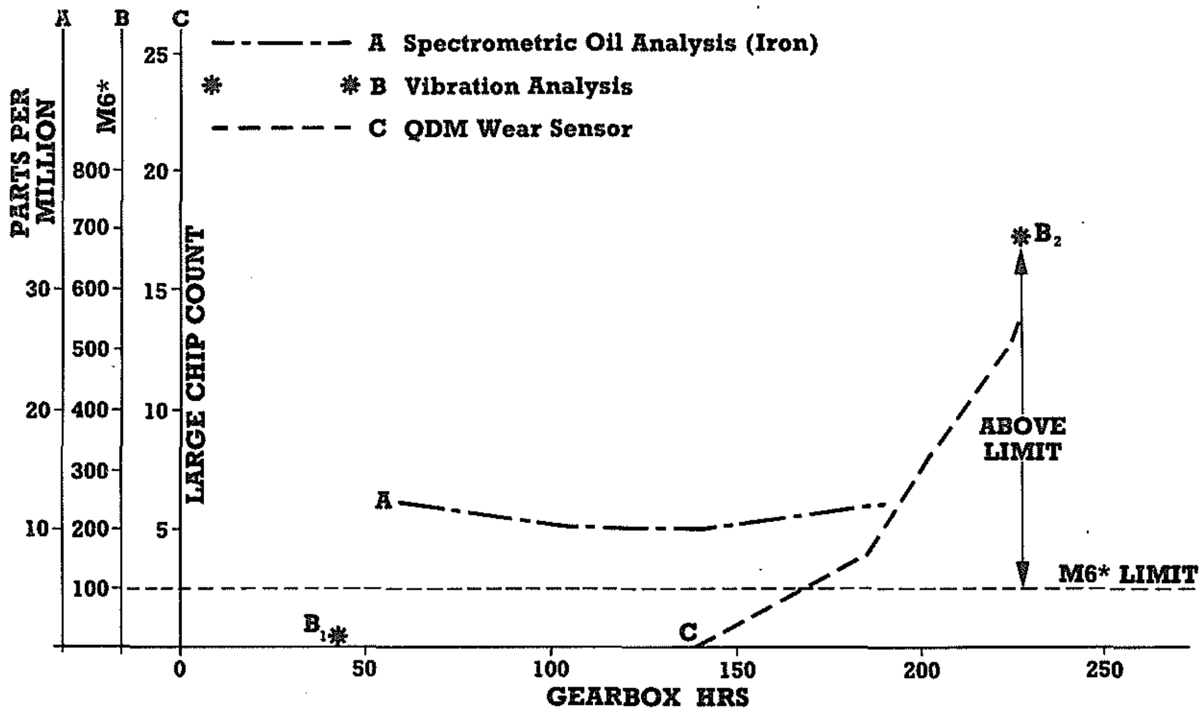

Fig 4. Vibration Health Monitoring Results

Range of M6* values to July 85 (with high value cases segregated) (1643* values from 106 different G/B fits on 17 A/C & over 14,616 A/F hrs)

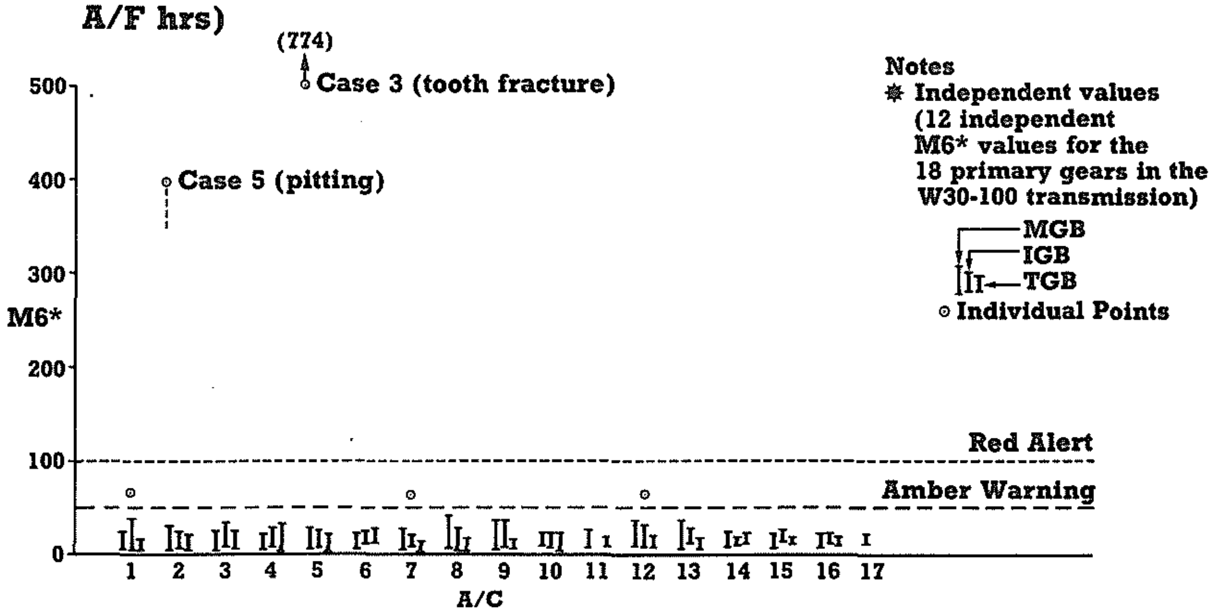

Fig. 5 Vibration Analysis Result for Case History No. 3 (tooth fracture)

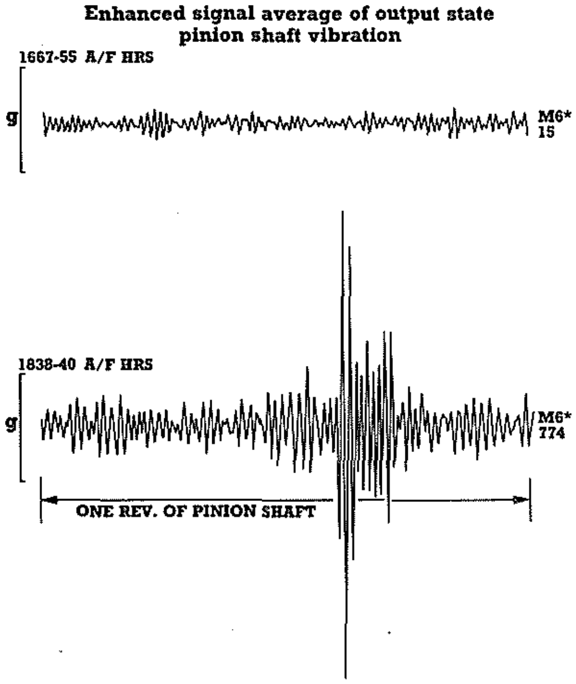

Fig. 6 Main Rotor Gearbox Case History 4
(Development Test Bearing Liner Spinning)

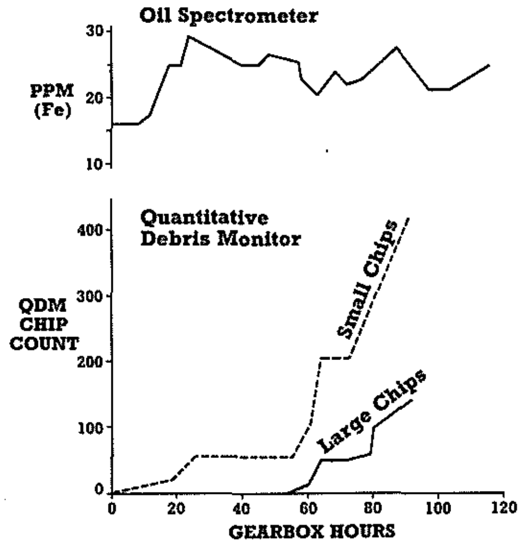

Fig. 7 Main Gearbox Case History 5 (Development test — light pitting)

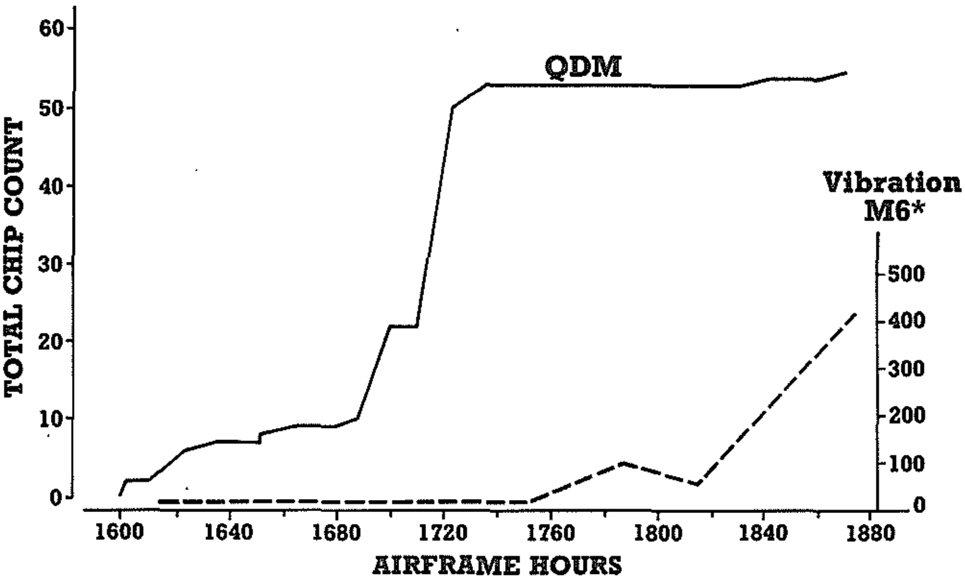

Fig. 8 Portable Vibration Analyser produced by Smiths Industries to Westland Specification.

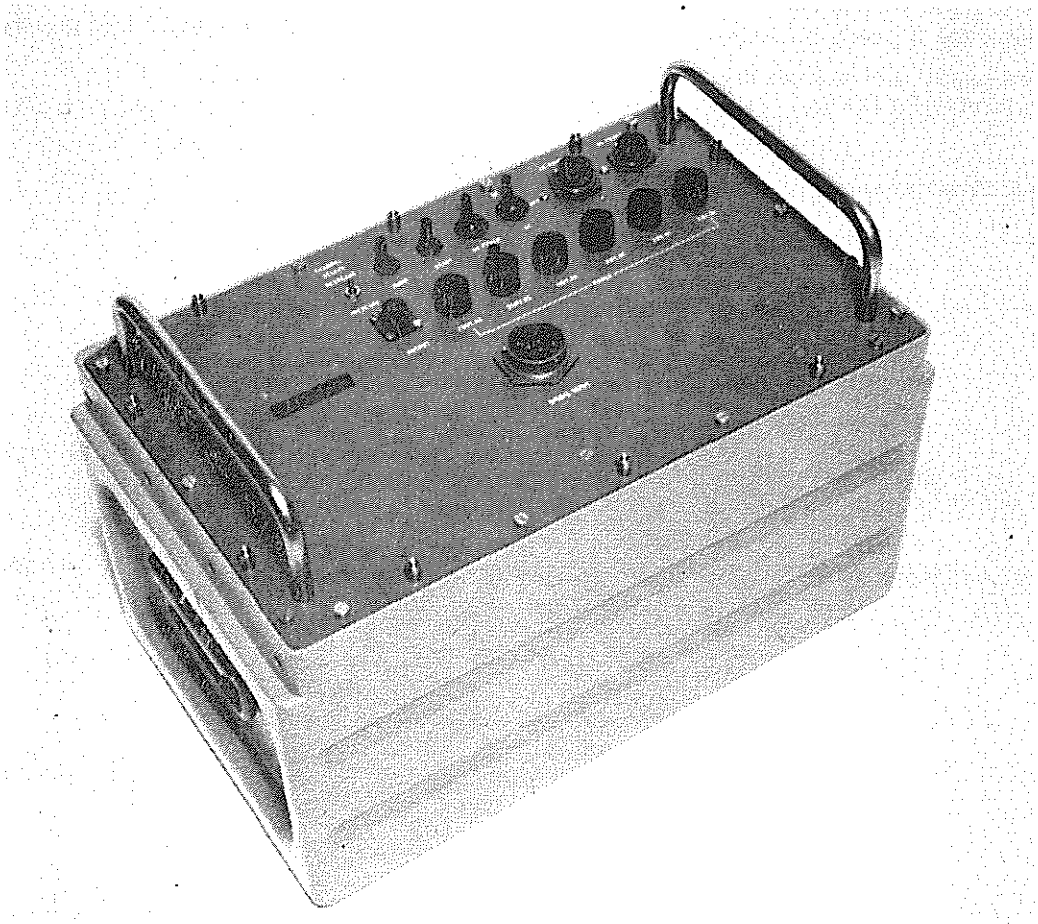

Fig. 9 Summary of Case Histories

CASE HISTORY		DAMAGE FOUND	SYSTEM INDICATION FOR REJECTION
1	Main Gearbox (In Service)	Light pitting of output gears	Q.D.M. above limit S.O.A. above normal trend
2	Main Gearbox (In Service)	Tooth fracture on output pinion	Q.S.M. above limit Vibration M6* value above limit
3	Main Gearbox (In Service)	Pitting of input Bevel wheel & pinion	S.O.A. above limit HM Systems not used by Operator
4	Main Gearbox (Development)	Lower hub bearing spinning	Q.D.M. above limit
5	Main Gearbox *(Development)*	Light pitting of output *Pinion*	Q.D.M.—high chip count *Vibration M6* above limit*