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HEALTH AND USAGE MONITORING IN HELICOPTERS

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ABSTRACT

In a Westland paper at the 1982 European Rotorcraft Forum, advances in the health monitoring of helicopter gearboxes were presented. This paper addresses the health monitoring of all helicopter systems and the concepts and applications of usage monitoring. Service experience with the advanced transmission health monitoring techniques on the Westland 30 helicopter is described.

Implementation of engine performance monitoring, low cycle fatigue and creep, and transmission torque monitoring are discussed. Recent advances in sensors, algorithms and analysis systems, both airborne and ground based systems, are presented. The problems relating to health and usage monitoring of helicopter rotor systems and structure are outlined. The comprehensive on-board monitoring and analysis systems designed for the W30-300 and the EH101 are described, together with certification issues and maintenance data handling requirements.

1. INTRODUCTION

Aircraft availability is of vital importance to operators whether civil or military - implying that all systems must be functional when an aircraft is required for operation and that no components have been "borrowed" in order to keep a sister ship flying. There are two key factors in satisfying this requirement - high reliability of all components and the ability to predict impending unserviceability in each "Line Replaceable Unit". Amassing spare parts is not a solution acceptable to many operators either from cost or from logistics considerations. Many recent technology developments offer step increases in life and reliability: in engines - single crystal turbine blades, improved blade attachment, reduced number of components, reduced turbine entry temperatures, improved bearing locations and materials; in transmissions - parallel shaft gear layouts, improved materials, lubricants, seals and fine filtration; in rotor systems - composite blades and rotor heads; in hydraulic systems - improved manufacturing techniques; in electrics and avionics equipment - improved sensor and connector technology and developments in amplifier and integrated circuit technology. But all this is not sufficient - there will remain components with finite lives whether due to increased stress levels to save weight, operational load exceedances, maintenance induced damage or due to random shortcomings in quality control or housekeeping. There is always likely to be a dispersion in usable lives of components, whatever improvements are achieved in design, materials and manufacture. Therefore effective means of continuous assessment of defect development (i.e. health monitoring) and life consumed (usage monitoring) will always be required. This paper reviews developments in health and usage monitoring systems successfully introduced into the Westland 30 series 100 helicopter, together with plans for their enhancement in growth versions of the Westland 30 and in the EH101 helicopter, a collaborative project with Agusta.

2. HEALTH MONITORING PROVISIONS IN THE WESTLAND 30 SERIES 100 HELICOPTER

The philosophy behind the package of techniques implemented in this transmission was described in Reference 1, together with details of two techniques introduced to helicopter main transmissions for the first time - the Quantitative Debris Monitor and Vibration Analysis. These are tabulated in Figure 1.

It is important for maintenance planning purposes to be able to follow the development of progressive surface wear modes long before rejection is justified. Spectrographic oil analysis has traditionally served this function and more recently the Ferrograph has supplemented the spectrometer. Westland has continued to apply these techniques to the Series 100 helicopter during its development phase and is thereby able to advise operators on the interpretation of oil analysis results. The "small chip" counting facility of the Quantitative Debris Monitor (QDM) also serves this function but provides instant information at the aircraft, obviating the time delay and the vagaries of oil sampling and of filter performance relating to oil analysis. If surface wear progresses to a stage at which component removal is justified it is important to be able to determine this with some accuracy - to prevent premature rejections on the one hand and prevent diminution of safety margins on the other. Magnetic plugs, fitted to all gearboxes on the Series 100, have served this function very effectively for many years. They do however require skill and experience in assessing the significance of debris caught, and, because they are removed from the gearbox sump for inspection, particular care is required in the design and maintenance of oil sealing features. The QDM system fitted to the Westland 30 Main Rotor Gearbox is a remote-indicating system with output displays mounted in an avionics bay, readily accessible for after-flight inspection. Particle detection thresholds are set such that the "large chip" counting circuit responds only to debris mass relating to advanced wear/rejection conditions. The quantitative nature of the system plus the detection size threshold control are both considered essential for accurate assessment of rejection condition.

Fracture modes are rare occurrences, thanks to well established design procedures and to exhaustive component testing. Nevertheless the potential consequences of gear fracture are such as to justify employing the means of detection. Vibration analysis techniques have been developed at Westland specifically for this purpose. Permanently mounted accelerometers and cables are a feature of the Series 100 helicopter and data is recorded during a brief period of ground running using a portable multi-channel recorder connected to a sampling connector. Fast response ground-based analysis facilities produce quantitative outputs capable of unequivocal rejection criteria. A further facility added to the Series 100 transmission is that of borescope inspection. Blanks can be readily removed from specially provided ports in the casing of the main transmission and guide-tubes inserted to enable a flexible borescope to be directed precisely to each gear within the box. Thus if any marginal indications should arise from any of the health monitoring systems borescope inspection can be carried out without removal of gearboxes from the aircraft.

The Rolls Royce Gem engines that power the Series 100 helicopter are fitted with magnetic plugs in each oil scavenge line.

Experience to date covers 3000 hours of flying and ground running on nine aircraft and several hundred hours of gearbox rig testing. Vibration data has been collected from seven aircraft and processed - the health index values versus gearbox hours for eight gearboxes are summated in Figure 2. None of the values exceed a level of 20, the rejection level being 100. This plot is for one particular gear but is typical of that for all gears in this transmission.

Vibration analysis successfully detected distortion in a used gear which was reassembled in a main rotor gearbox and fitted to a development aircraft, and detected gimbal wear in an engine-to-gearbox coupling, although this was within acceptable limits. The Quantitative Debris Monitor output has remained within normal operating limits for all gearboxes with the single exception of the first ground run of the development programme. A fretting incident occurred in the main rotor gearbox to which the QDM small chip count responded immediately, as did spectrographic oil analysis (Figure 3).

The wear mode was benign in the sense that it was unlikely to jeopardise continued running; also a design modification to cure the defect was being evaluated in a concurrent test on another gearbox - the ground run was therefore continued. The localised defect deteriorated with further running and at 56 hours the QDM large chip count responded and increased rapidly until the test was stopped at 145 hours. Had this been a service gearbox it would have been rejected on the basis of the QDM results at 57 hours. The *spectrographic oil analysis results did not* follow this further degradation in condition which was characterised by a dramatic increase in large particles and consequent improved filtration performance of the oil filter. The direct reading Ferrograph also did not follow this worsening of condition, in fact the readings fell to near zero from 60 hours onwards. Figure 4 is a summation of the spectrographic oil analysis results (iron) for three main rotor gearboxes and represents normal running

3. HEALTH AND USAGE MONITORING SYSTEMS PLANNED FOR WESTLAND 30-160, -200 AND -300

3.1. Westland 30 Series 160 Helicopter

Plans are well advanced for the introduction of an on-board computer on this helicopter for which Rolls-Royce Gem 60 engines are the selected power plant. The techniques to be used cannot be said to be new. In fact they are precisely those used for the original design of the helicopter. What is new is that the techniques are applied continuously on the aircraft using real measured data. In the original design case calculations can only be done based on assumptions which must of necessity veer heavily towards the pessimistic because of flight safety factors.

It is perhaps worthwhile to make a brief consideration of the design assumptions in order to realise the potential benefits of the application of usage monitoring. In the case of both civil and military customers an aircraft will be purchased against a particular operational requirement. The civil customer will assume use on a particular route with number of aircraft related to frequency of service and loading factors. The military customer will purchase, or have an aircraft developed, for a mission spectrum relating to a "hot war" situation. Due to the inherent flexibility of helicopters in both cases they are unlikely to operate to these "design" requirements for a significant percentage of the helicopter life. It can easily be seen that by monitoring the major areas it is possible to assess the true usage of life limited components.

The computer, being produced to a Westland specification by Dowty Electronics, will perform:-

a) *Engine power monitoring*

b) Engine usage monitoring

c) Transmission exceedance monitoring

d) Transmission usage monitoring

e) Rotor usage monitoring.

The unit is a small interseat console mounted device. (FIGURE 5)

The hardware employs CMOS technology with a NSC 800 processor. Relevant usage numbers are stored in non-volatile memory whose write cycle is short enough to enable the stores to be updated as the unit powers down.

The software is written in Z80 Assembler and is documented to Westland Software Standard ESD1082, a documentation system compatible with RTCA-DO-178.

Due to the low power consumption of the CMOS technology a linear power supply is used, easing EMC design considerably, in fact highest power consumption is when the display is energised.

The unit includes comprehensive built-in-test to assure the integrity of all calculations.

To perform the required calculations the unit requires inputs of:-

1) Outside Air Temperature

2) Pressure altitude

3) Rotor Speed

4) Engine Torque for each engine

5) Engine Free Power Turbine Speed for each engine

6) Engine Gas Generator Speed for each engine

7) Engine Power Turbine Inlet Temperature for each engine.

It is a mandatory requirement that all these parameters are displayed to the pilot. In anticipation of these health and usage monitoring requirements the Air Data Computer and Cockpit Instruments already incorporate the required outputs:-

a) Engine Performance Monitoring - two algorithms are used, one related to Gas Generator Speed, the other to Power Turbine Inlet Temperature.

   The polynomials, provided by Rolls-Royce, are precisely those used to generate the nomographs that are provided in the aircraft manual for manual measurement of engine performance. An engine is delivered with a 4% power margin and must be rejected in civil use when there is no power margin. It is very important to the civil user that the method used is as accurate and repeatable as possible.

b) Engine Usage monitoring - The Algorithms used for both the Gas Generator and Power Turbine stages are both simplified types of Low Cyclic Fatigue calculation. The maximum and minimum speed of all major accelerations and decelerations are recorded during flight. From these the major cycle can be identified, and the damage of the minor cycles is calculated using a look-up table. In order to retain certification of an aircraft the civil customer is currently required to operate this procedure manually on representative flights.

c) Transmission exceedance monitoring - In order to have the ability to extend the maximum continuous power (or 100% Torque Figure) it becomes necessary to monitor exceedances above the 100% figure. The reason for this is that by moving the 100% figure closer to the Fatigue damage limit, the usage of Fatigue Life at an exceedance becomes significant. Whilst the 100% figure is well below the fatigue damage limit the usage due to exceedances can be treated on a statistical basis. Using the statistical basis the maximum continuous power is 1960 SHP, with recording of exceedances of 2100 SHP. By dividing the torque (0 to 180%) into bands the time in each band is recorded. For the bands above 100%, dependent on the size and time of an exceedance, the maintenance personnel will be able to determine the required procedures.

d) Transmission Usage Monitoring - The torque path is clearly defined in the gearbox, as are the Fatigue Damage limits for each gear. Using the times recorded in the transmission exceedance monitoring, for each important gear these times can be converted to gear usage. As some gears transmit power from port engine, starboard engine or port and starboard engine, the time bands for each case are accummulated. It is possible to assess the maintenance action required by the proximity of the gear usage figure to the limiting value.

e) Rotor Usage Monitoring - This can be most easily assessed by monitoring the torque spectra into the rotor. Part of the head has a life dependant on speed reversals. This is monitored by recording the maximum and minimum torque and the number of torque reversals.

3.2. Westland 30 Series 200 Helicopter

General Electric CT7 engines have been selected to power this aircraft and flight testing is underway in a development aircraft (aircraft code G-ELEC). The General Electric mechanical History Recorder will be supplied with the engine but the Westland/Dowty computer will also be fitted for computing engine power monitoring, additional engine usage monitoring and the transmission and rotor system usage monitoring provisions detailed in para.3.1. For engine bearing wear detection, contact-bridging type electrical chip detectors are currently fitted. Several engine manufacturers are evaluating the Quantitative Debris Monitor system as currently fitted to the Westland 30 transmission, as an alternative to simple magnetic plugs or electric chip detectors and it is possible therefore at some future date that engines and transmission could commonise on this system. The helicopter transmission is extended on the Series -200 to account for the higher input speeds of the CT7 relative to the Gem 60's - additional two-stage speed reducing stages are added to the inputs of the main rotor gearbox. The existing MGB oil system is extended by an additional pump and cooler to provide a common oil system. Super fine filters are fitted to this oil system, likewise on the engine oil system. The likelihood of surface wear modes in engines and main transmission should therefore be greatly reduced, although the effectiveness of oil analysis techniques for early warning of such could be diminished (reference 2). However the QDM small chip count function in the transmission is expected to fulfill this need - no wear problems have been encoutered on transmission rig or flight testing with this filter fitted, so it is not possible to confirm the relevance of the the experience described in reference 2. A monitor filter has also been developed as part of the main filter unit to back up the QDM small chip count in relation to non-ferrous particles.

The hardware of the Westland/Dowty computer is identical to that used on the Westland 30 series 100-60. The only difference being in the software for the engine performance and usage monitoring as follows:-

a) *Engine Performance Monitoring* - Due to the different Thermodynamic design of the CT7 engine, there is only one performance algorithm, based on the Power Turbine Inlet Temperature.

b) Engine Usage Monitoring - The GE Engine History Recorder already monitors:- Low Cycle Fatigue from Engine running hours and major and minor cycle counting; and thermal creep from a power turbine temperature weighted time count. Additional monitoring is achieved by recording the maximum gas generator speed and temperature.

3.3. Westland 30 series 300 helicopter

The extensive range of health and usage monitoring provisions on the earlier aircraft will be enhanced further by means of a greatly extended dedicated on-board computer. This will permit on-board processing of gearbox vibration health monitoring data, pilot warnings of impending system failures and of limit exceedances, in addition to enhanced maintenance aids for between flight inspections, and for fleet wide maintenance data management. The transmission will be provided with QDM sensors in all gearboxes and small and large chip counts will be fed to the computer. The transmission and rotor system usage monitoring provisions will be extended.

The hardware consists of a pilot display of similar size and nature to that of the Westland/Dowty unit. This is connected to a ½ ATR size computer via ARINC 429 links. The use of such links allows the information to be transmitted to an integrated avionic system, on military systems, removing the need for a stand-alone display or to Electronic Flight Instrument Systems (EFIS) to allow for more sophisticated pilot displays. As the unit accummulates a much larger quantity of information than the 30-100/60 or -200 a ground data retrieval unit is included as part of the system interfaced by a standard serial computer interface.

The engine monitoring is extended to include parameter exceedance monitoring relieving the pilot of this task. Provision is also made for more complex usage monitoring if this is required by the engine manufacturer.

On the transmission incorporation of a tail drive-shaft torquemeter using FM telemetry techniques, allows the torque exposure of the intermediate and tail gearboxes to be monitored. This should give great benefit as the variation of tail rotor power during manoeuvres and due to wind is very great. It also allows the lives of gears related to main rotor power to be more accurately assessed.

The algorithms to be used will be the same as the earlier W30 aircraft but the torque spectra will be divided into more bands.

In addition to the accelerometers fitted on the -100 series, charge amplifiers will be airframe mounted, reducing EMC problems, and the vibration analysis techniques performed in the computer. The signal averages of the vibration "snapshot" will be available for ground retrieval.

A rotor head monitoring system is in the early stages of development. Strain gauges are to be mounted on the critical parts of the head. The strain gauge signals will be transmitted to the computer via an FM-telemetry system. Using the strain signals related to the rotor azimuth signal it will be possible to display a head moment indication to the pilot during taxi manoeuvres.

4. HEALTH AND USAGE MONITORING PROVISIONS IN THE WESTLAND/AGUSTA EH101 HELICOPTER

Due to the entirely different role of the EH101 to the Westland 30 it has a much more sophisticated avionic system in both its civil and military roles. The centre of this system in both cases is the dual-redundant Aircraft Management Computer. These computers perform control and display management, navigation, communication management as well as health and usage monitoring.

The dual redundant architecture improves the data integrity and should allow greater improvement in usage monitoring and health monitoring early warning to the crew. It is planned to fit the AMC to all development aircraft, coupled with the instrumentation recording and test rig data from over 3000 flight hours, algorithms will be developed and proved in many areas. The aim for EH101 is to eliminate the need to life components on flying hours alone. To this end the engine monitoring is dramatically increased and the system also incorporates airframe usage monitoring.

Responsibility for the various areas of health and usage monitoring is part of the component design. Design leadership of the AMC lies with Agusta, who will also be writing the software for health and usage monitoring. For the updating of navigation components and radio presets the system already includes a data transfer device, a pocket-sized memory store. This device will also be used for the retrieval and updating of health and usage monitoring information.

5. CERTIFICATION AND DATA HANDLING

The complexity and scope of health and usage monitoring applied to each of the aircraft is largely dependent on the amount of development flying available. In the case of W30-100-60 and W30-200 these can be viewed as engine programmes only. The algorithms employed are simple and can easily be checked by manual logging. The testing required by software certification procedures such as RTCA-DO-178 give a high degree of confidence in the application of the algorithms that are already proven, i.e. in the case of 100-60 these being engine power monitoring and usage monitoring. In the case of new algorithms these can be checked during periods of extended running such as the tied-down transmission type test,a 200 hour programme. In the case of the W30-300, where a new 5-bladed bolted rotor head is being developed this enables the development and validation of new techniques for the monitoring of the rotor head.

In the case of EH101 with over 3000 hours of flight testing the ability to explore, develop and validate techniques in many areas is to be used to the greatest potential. Firm objectives have been set however to reduce the risk of effort being extended on areas where the benefits are small.

In all cases the effect of failure of the system must be clearly understood and lead to a well defined action in order that a realistic usage figure is assumed for the inoperative period. The safest way to ensure this is by a ground data-base of the usage data. Changes in rates of component usage can then be related to aircraft usage. This enables trade-offs at system failure to be established and erroneous recording easily identified.

It is the intention on EH101 that Westland/Agusta maintain a comprehensive data base of aircraft data to enable the extension of component lives, to an eventual usage life limit only, in the shortest possible time. It is planned that this data base would interface readily with those generated by customers.

6. SUMMARY/CONCLUSIONS

The range of health and usage monitoring facilities being developed for the Westland 30 family of helicopters and the Westland/Agusta EH101 represent a major technology development contributing significantly to increased usable life of major components, enhanced flight safety, accelerated growth in Mean Time Between Removals, reduced maintenance workload, and reduced aircraft down-time. All these factors combine to offer significant improvements in aircraft availability, which is of major interest to operators, both commercial and military. The provisions include techniques which Westland have developed such as vibration health monitoring of gearboxes and rotor system usage monitoring, and systems developed in close collaboration with others - such as the Quantitative Debris Monitoring System with TEDECO, and the maintenance computer with Dowty Electronics. Fine filtration of gearbox oil is another life extending feature introduced to these transmission systems, and one which has implications for fault detection, albeit in basically healthier gearboxes. Advances in computer technology, both in component size reductions and in reliability improvements, make possible the on-board processing of the comprehensive range of data proposed. On-board processing is essential for the life and safety improvements obtainable from limit exceedance indications, power checking and vibration health monitoring of fracture modes. It also makes possible significant reductions in between flight diagnostic checking and thereby reduces turn-round time and manpower costs. Operators of larger fleets can further process the data readily available for improved fleet management, and clearly they should now be giving thought to data and spares management systems to take advantage of this. Service experience with the advanced package of transmission health monitoring techniques applied to the Westland 30 Series 100 helicopter has been very encouraging, and clearly operators will be wise to take full advantage of these provisions.

REFERENCES

1. Derek G. Astridge: Health Monitoring of Helicopter Gearboxes. Presented at the Eighth European Rotorcraft Forum, Aix-en-Provence, France, September 1982.

2. Dr Thomas Tauber et al: Fuel Flow Debris Monitoring and Fine Filtration for Helicopter Propulsion Systems. Presented at the Rotary Wing Propulsion System Specialist Meeting of the American Helicopter Society, Williamsburg, VA, November 16-18, 1982.

REQUIREMENT	NEW METHODS	TRADITIONAL METHODS
MONITORING PROGRESSION OF SURFACE WEAR MODES	QUANTITATIVE DEBRIS MONITOR - SMALL CHIP COUNT	OIL ANALYSIS (SPECTROGRAPHIC & FERROGRAPHY)
GEARBOX REJECTION PARAMETER FOR SURFACE WEAR MODES	QUANTITATIVE DEBRIS MONITOR - LARGE CHIP COUNT	MAGNETIC PLUGS
GEARBOX REJECTION PARAMETER FOR FRACTURE MODES	VIBRATION ANALYSIS	NONE (TRANSMISSION FAILURE)
ON-AIRCRAFT INSPECTION OF INTERNAL COMPONENTS	BORESCOPES & GUIDE-TUBES	NONE

FIGURE 1

SUMMARY OF GEARBOX HEALTH MONITORING PROVISIONS ON WESTLAND 30 SERIES 100

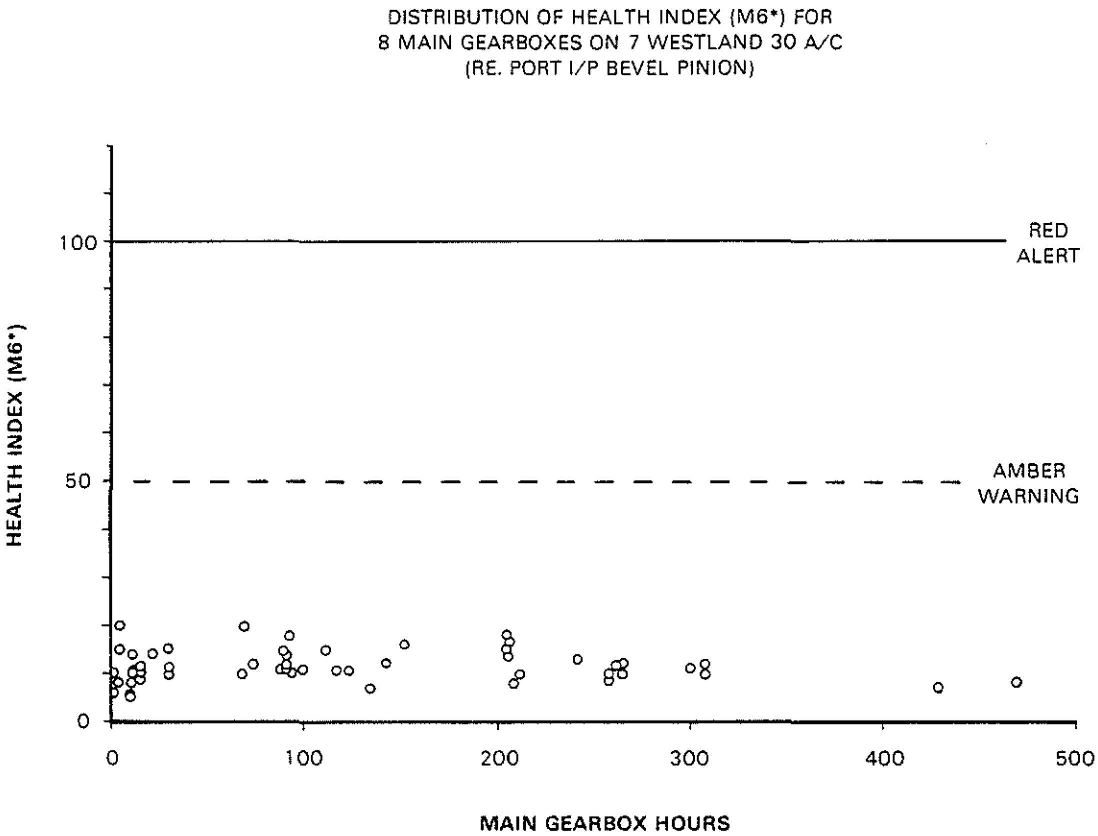

FIGURE 2

SUMMARY OF VIBRATION HEALTH MONITORING INDEX (M6*) FOR WESTLAND 30 SERIES 100

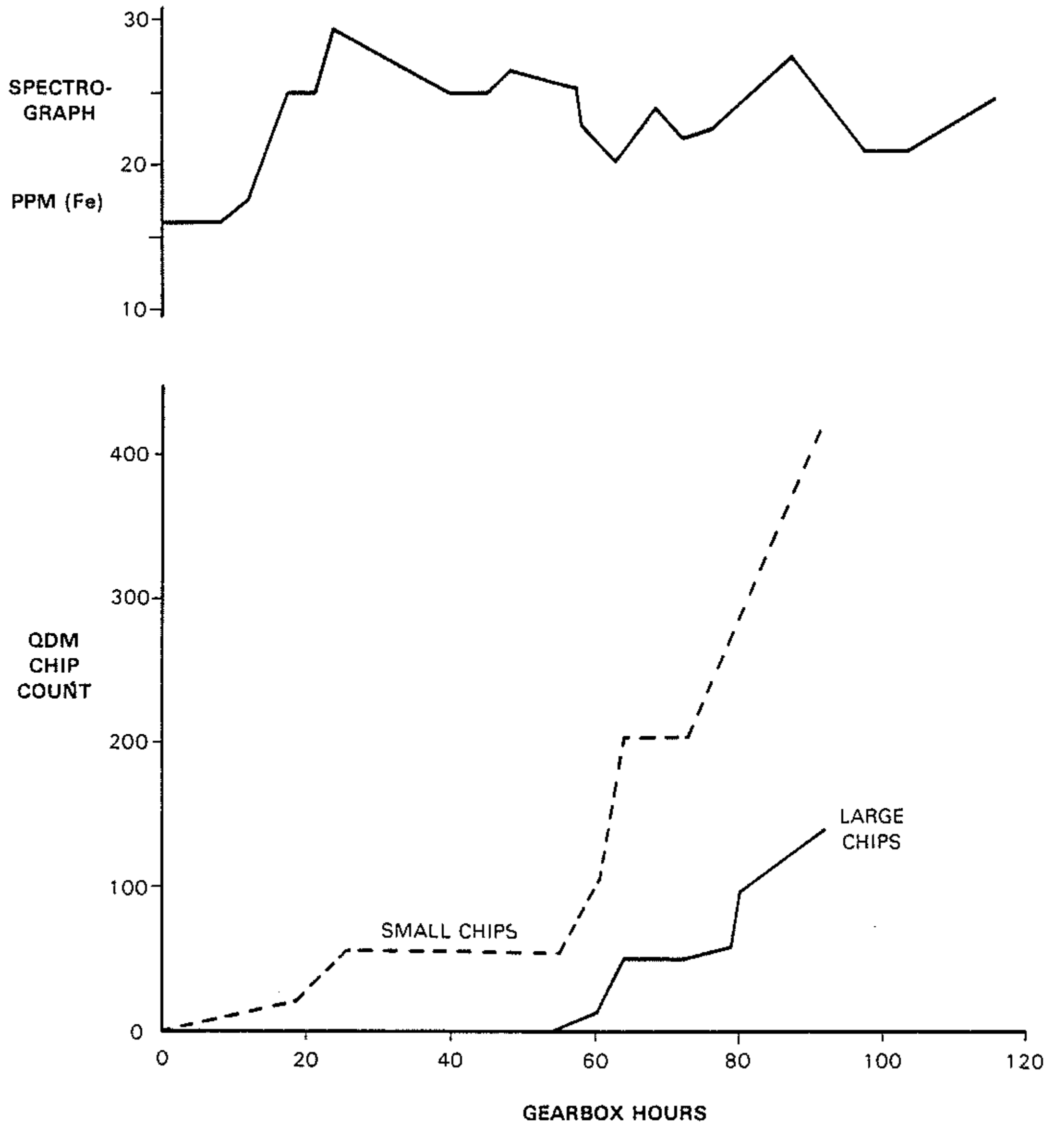

FIGURE 3

QDM & SPECTROGRAPHIC OIL ANALYSIS
FOR FIRST GROUND RUN OF WESTLAND 30 SERIES 100

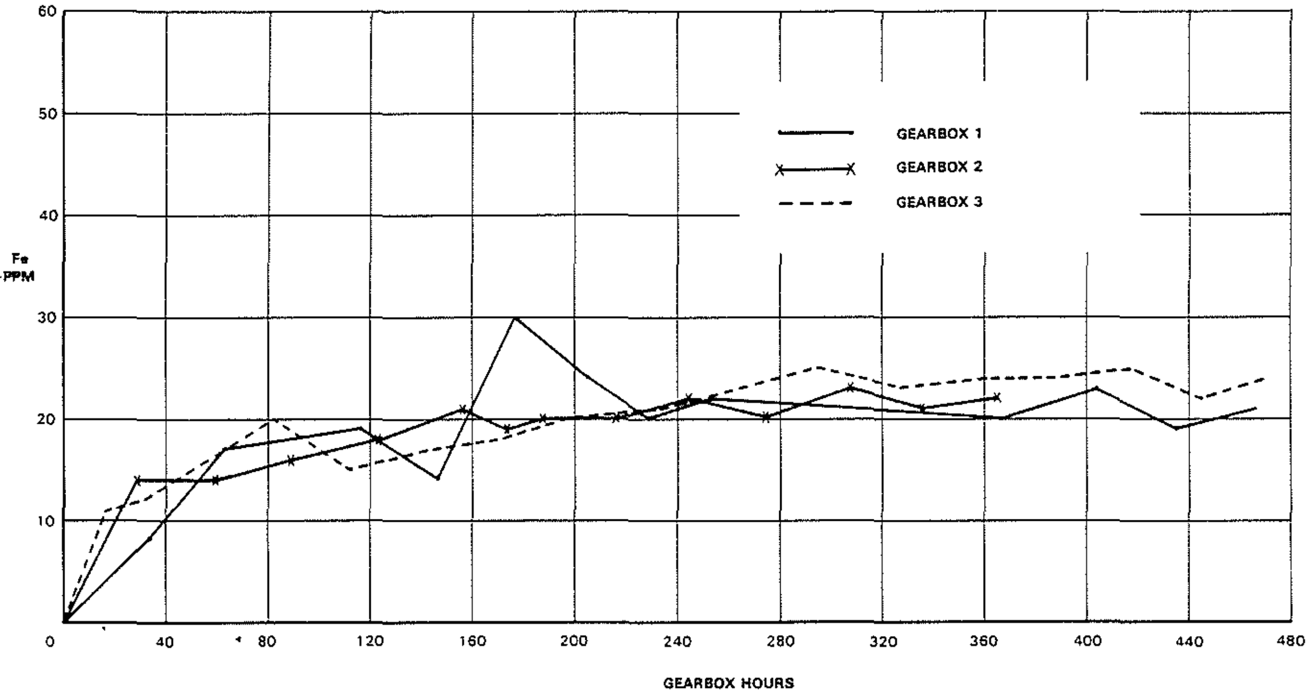

FIGURE 4

WESTLAND 30 MAIN GEARBOX - OIL ANALYSIS/IRON CONTENTS

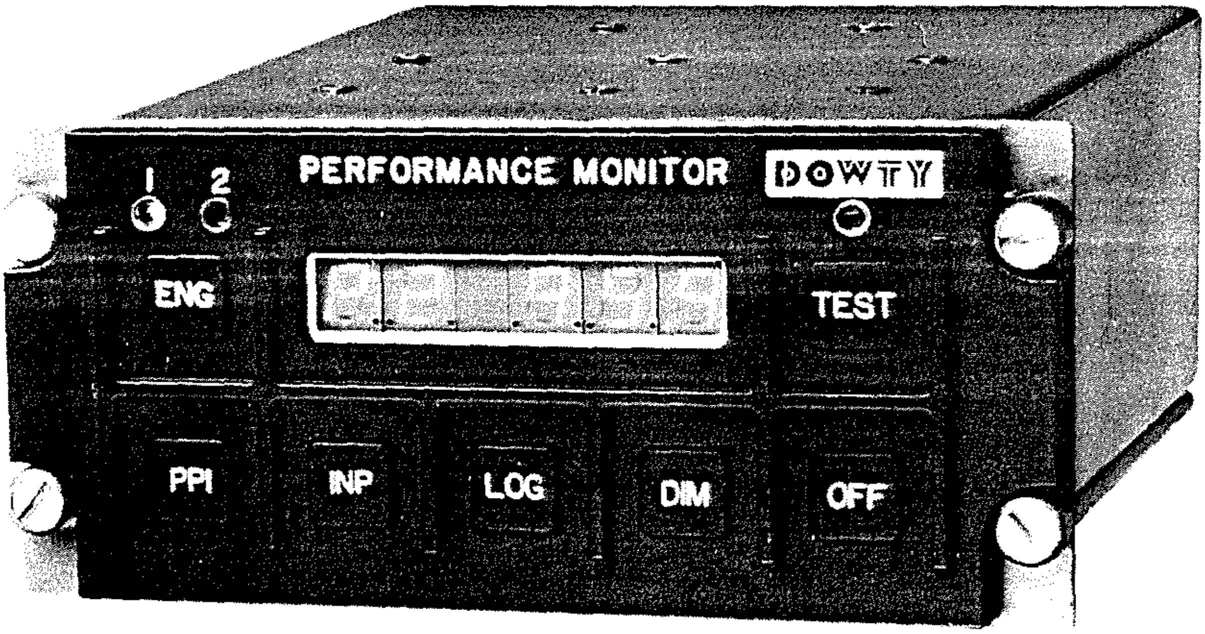

FIGURE 5

DOWTY COMPUTER