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THE INTEGRATION OF HEALTH MONITORING TECHNIQUES FOR HELICOPTER GEARBOXES

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ABSTRACT

This paper discusses the use of a combination of health monitoring techniques to provide comprehensive coverage of possible failure modes in a typical transmission gearbox. From experience gained in research and development work sponsored by the UK Ministry of Defence in recent years, the paper explores the relative value of conventional status parameters such as oil level, pressure and temperature, together with the newer techniques of wear debris and vibration analysis.

The use of health monitoring techniques in a matrix to provide both early warning of failure and diagnostic information is considered, as well as the effect of design features such as transmission configurations, oil filtration standards and filter bypass arrangements. The problems of data collection and processing are also discussed.

The development of the Anglo Italian EH 101 Health and Usage Monitoring System is used to illustrate the process of sensor location, validation of processor algorithms and the planning to achieve full system certification.

1. INTRODUCTION

The ability of designers to include redundancy features to improve the safety of current helicopter transmission systems is constrained by weight considerations. Whilst two or even three engines can share the load, and provide acceptable engine out contigency performance to recover safely from most of the critical flight conditions, there remains little scope for the duplication of main and tail rotor transmission paths, so that here, airworthiness depends heavily on gearbox and drive shaft reliability.

2. THE PROBLEM

For a new helicopter design, the development programme of accelerated transmission rig testing and test flying serves to establish initial gearbox reliability and give evidence for airworthiness certification. During this process, gearboxes are examined to check their condition against the list of likely failure modes in all components, from previous experience, especially gears, bearings, seals and lubrication paths. Data on the limiting failure modes is obtained by deliberate tests to failure. At the end of the process however, the prudent designer will admit that however successful his development programme, a finite chance remains of unexpected failure in later service because not all of the test parameters are within his control.

The symptoms of a few of these failures may be genuinely missed due to testing inadequacy, but it is a safe bet that the majority of those will occur because the conditions under which the gearbox will operate in service will change in some small, but significant way from those present in the controlled development programme. These changes can be summarised in 4 categories as follows:-

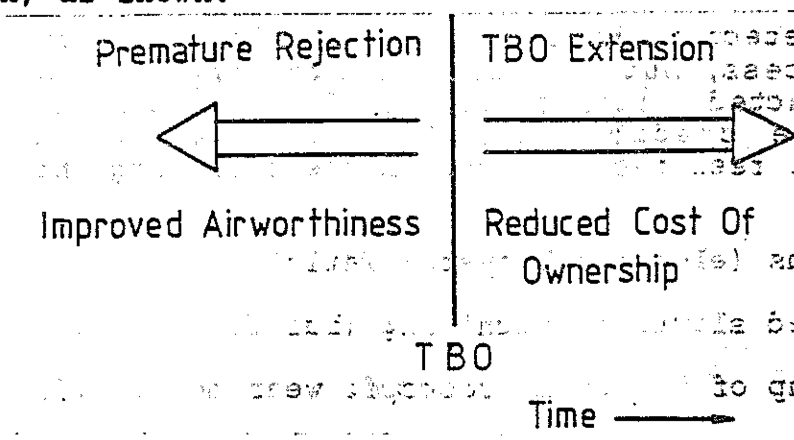
a. Failure of Quality Assurance: Material changes, component supply variability, production methods and tests.

b. Operating Conditions: Loads spectra and operating environmental factors eg. climate.

c. Maintenance practices: Errors in assembly, eg. overtightening of bolts or misrouting of pipes and cables. Inadvertent damage during servicing. Lubricant contamination.

d. External factors: The vibration environment. Misalignment between adjacent mechanisms.

The reality of this problem is best illustrated by the snapshot of failure records from in service Civil helicopters on the UK register between January and June 1981, showing the larger proportion of transmission system failures (Figure A). An example of the approximate breakdown of failure modes with a typical gearbox (in this case the Sea King Mk 5) is shown at Figure B. This problem gives rise to the need for an effective health monitoring system, which may be viewed as having a dual application, as shown:



For a typical gearbox in service, a Time Between Overhaul (TBO) has been established at the vertical line shown. If the current records show that gearboxes are failing to reach the figure due to mechanical defects, then the health monitoring system is needed to predict failures and thereby avoid accidents, ie. improve airworthiness. On the other hand, if most gearboxes achieve TBO, the opportunity arises within ultimate fatigue limits, to extend the TBO 'on condition' bringing longer service life and reduced costs. A similar situation exists during development and early life of the gearbox, where the health monitoring system can assist in accelerating the extension of an initially ultra conservative TBO.

3. EXISTING TECHNIQUES

Until recently, the main on-aircraft techniques for gearbox health monitoring on UK Military aircraft have been pressure and temperature gauges in the cockpit, and electric chip detectors. Periodic vibration surveys using portable accelerometer equipment giving a plot of frequency spectrum against velocity have also been used for comparison with the established norm, and for trend monitoring. The main function of pressure and temperature gauges is to monitor the lubrication system. Most abnormal temperature indications (discounting false readings) show cooling system faults such as bypass valve failures and blocked coolers, whilst low pressure warnings usually mean clogged filters, oil pump failure or loss of oil due to seals, casing failure or burst pipes. It is comparatively rare for abnormal p's and t's to indicate other gearbox faults such as bearing distress. When this occurs, the system usually turns out to be a poor predictor, giving indications only at a very advanced state of failure, if not simultaneous with actual failure, accompanied by other major symptoms such as heavy vibration, or noise.

There is a good case of course for adding remote oil level sensors in this area, since a significant number of lubrication failures occur after steady loss of oil over a period of minutes, or even hours in flight, and remain undectected until pressure failure occurs, however the UK Services have not yet employed these devices.

Electric Chip detectors have made a valuable contribution to the monitoring process, but the early 'remote indicating mag plug' types have attracted a poor reputation for spurious warnings, and have lost some credibility. This is because nearly all indications have resulted from one of the following three causes:

a. Spurious (electrical system fault).

b. Isolated sliver of machining (build) debris.

c. Build up of benign microscopic wear debris (fuzz).

Periodic monitoring of the simple frequency vs velo[illegible] of the gearbox with portable equipment has be[illegible] some value in tracking fault progression, and diagnosing faulty components eg. bolt on accessories such as generators, or hydraulic pumps, but generally an obviously abnormal vibration is needed to alert the operator in the first instance. Warnings therefore arrive late in the process and may be missed altogether if the fault develops between sample intervals.

This gives rise to the clear need for improved techniques. Fortunately, rapid advances have been made recently in several areas of health monitoring, especially the following:

Pulsed electric chip detector.

Quantitative debris monitor.

Digital signal processing of vibration data.

Shock pulse monitoring.

Debris indicating screens.

Before examining any of these more closely, the ideal requirements of the monitoring system should be considered, and these are:-

4. HEALTH MONITORING SYSTEM REQUIREMENTS

An effective health monitoring system should provide:-

DETECTION

- Advanced warning of failure modes.

DIAGNOSIS

- Indication of faulty component.

PROGNOSIS

- Prediction of useful life remaining.
- Clear rejection criteria for developing faults.

FOR DETECTION, the ideal parameter measured by the monitoring system is sensitive to change in condition, non dimensional and independent of test conditions, such as gearbox rpm and power level. The parameter should also give a 'one shot' indication, where no reference is needed to historically determined 'trend' data.

FOR DIAGNOSIS, the ideal parameter will not only indicate the component at fault in a complex gearbox, but also give some visibility of the condition of serviceable components for confidence.

FOR PROGNOSIS, the requirement is reliably to predict how much good time there is left to failure. The ideal parameter will remain sensitive to change in condition throughout fault progression, and exhibit a near linear progression characteristic.

In reality, the characteristics of parameters from any particular monitoring technique will fall short of these stated ideals, and will not cover all the fault modes anticipated by a design audit or discovered during development. However, examination of the characteristics of a variety of techniques will enable the initial choice to be made of a small number of monitoring techniques to give the most cost effective coverage for the available budget. The precise response of each monitor to faults will then be determined during development tests, where results can be correlated under controlled test conditions. Additional techniques should be included during this stage if alternatives exist to be decided on.

5. NEW TECHNIQUES

The Ministry of Defence has supported applied research at ISVR Southampton, Westland Helicopters and Stewart Hughes Limited over the past 10 years in advanced methods of vibration analysis deriving fault descriptors for gears and bearings by digital signal processing of the vibration data. The work has included research at RAE Farnborough. The vibration analysis section of the Naval Aircraft Materials Laboratory at Royal Naval Aircraft Yard, Fleetlands in Hampshire is currently assessing the results of a package of work in this area, whilst the Materials section, with expertise built up from operating the Royal Navy's Spectrometric Oil Analysis Programme, is closely monitoring developments in Oil Analysis and On-line debris monitoring techniques.

The most promising candidates for an effective integrated system emerging from recent work are considered to be vibration signal averaging, and full flow chip detectors with particle count and sizing capability. These techniques exhibit overlapping and complementary characteristics, and will now be examined as examples of real techniques for which the characteristics must be determined.

6. VIBRATION ANALYSIS - Signal Averaging

Practical experience in diagnosing gear faults has been obtained by Westland Helicopters from the periodic vibration monitoring programme on the Westland 30 as well as analysing archival data from fatigue substantiation tests. Seeded faults on the Royal Aircraft Establishment Farnborough gearbox test rig have been successfully identified for a Whirlwind epicyclic gearbox, and at Stewart Hughes Limited using a Rolls Royce Nimbus accessory gearbox.

The technique involves taking samples of the gearbox vibration signal from an accelerometer over a repeated time interval corresponding to the rotation of a particular gear or shaft using a tacho derived pulse. These consecutive samples of data are then added together and averaged in order to cancel the asynchronous events. The resultant noise rejection process produces a usable signal containing a clear pattern of gear activity ready for a variety of statistical processes. An example of the process is shown in Figure C. Stewart Hughes Ltd has listed the results of a number of these calculations (Figure D), as simple figures of merit (FM), although significant computer power is needed to process the test data.

The most experience from gearboxes in service, including notable success in identifying faults, has been gained by Westland's enhanced signal average technique using the parameter M6*, which is similarly derived to FM4A. Using the test rig at Royal Aircraft Establishment Farnborough (Figure E), Figure F shows examples of signal averages produced by seeded gear faults in an epicyclic gearbox during the Royal Aircraft Establishment's research work. Figure G shows an example of computed FOM FM2B for the seeded gear fault shown at Figure H.

A brief examination of the indications given by this family of parameters confirms that reality is far from the ideal expressed by the system requirements earlier. Firstly the indicators themselves exhibit varying sensitivity and patterns of response as a gear tooth defect progresses, and secondly, they must be used together to give maximum coverage. Figure I shows a typical pattern of responses for a gear tooth progressing from pitting, to spalling and ultimately to loss of teeth. FM4A, sensing localised impacts, responds vigorously when damage is slight. As the damage spreads to adjacent teeth, the FM4A reduces and does not respond again until single impacts of much higher energy level appear above a higher level of damage just before failure. On the other hand, the general detector (FMO) responds late. Sufficient information to meet the requirements of early detection, diagnosis and prognosis is available, but intellegent interpretation is necessary. These characteristics can be tabulated against the gearbox components and fault modes to determine the coverage so far, (Figure J).

For bearing fault signatures, promising research and development continues in the UK and elsewhere on a variety of vibration analysis methods, including shock pulse techniques and frequency spectrum analysis. However, bearing fault signatures are relatively difficult to extract from background noise, particularly in complex gearboxes, and problems exist due to the complex characteristics of the bearing to sensor transmission path and the effect on signals of slipping contact of the bearing rolling elements.

7. OIL DEBRIS ASSESSMENT

The Ministry of Defence acknowledges that considerable progress has been made in the USA with active chip detector improvements. Advances over the simple sump fitted splash type detector can be summarised as:-

CHIP DETECTOR ADVANCES

- Full flow positioning.
- Pulsed self cleaning (fuzz burn-off).
- Cyclonic debris separators.
- Debris sizing and counting.
- Provision for non-metalic particle capture.

An example of helicopter application is the TEDECO QDM system fitted to the Westland 30, in which two sizes of debris (>200µ and >1000µ) are counted. Figure K shows the resulting detection characteristics for small and large chips from records of a W30 tethered flight test of a main rotor gearbox to bearing failure. Ground analysis of contaminated oil and captured debris remains an important supporting activity for health monitoring, however results are effected by the oil filtration standard. Where 3 micron absolute standard filtration is employed in gearboxes, the efficiency of any Spectrometric Oil Analysis Programme (SOAP) will be reduced, since wear particles >3µ will be captured in the fine filter at first pass. However, it is considered that SOAP in selected instances may still prove useful for the detection of increased wear on non-ferrous components eg:

Shafts	-	Titanium
Spacers	-	Aluminium
Coatings	-	Silver
Casings	-	Magnesium

The detection characteristics of the advanced chip detector can also be added to the table of fault modes for components to produce the table at Figure L. For the list of faults tabulated, it can be seen that the integration of the two complementary techniques gives good coverage. In some cases, eg. bearing spalling, both techniques are capable of detecting the same fault mode, and so can be used as a cross check. For brevity, only detection has been considered, however in practice the capability for detection, prognosis and diagnosis will need to be considered.

It is not sufficient, however, to rely on health monitoring techniques that are aimed exclusively at detecting certain predicted failure modes, since unanticipated modes may always exist. Generalised parameters such as FMO, FM4 and small ferrous particle count should always be monitored to cover for the unexpected.

Once the choice is made for monitoring techniques, time intervals for the collection of data and threshold levels for caution (warning) and emergency (flight control) for each result will need to be determined from the development test programme data. The interval for periodic checking will be short enough to catch fault arisings before progression to threshold (maintenance action) levels, whilst threshold levels will be set high enough to avoid spurious warnings, and low enough to avoid catastrophic failure by a sensible margin.

8. EQUIPMENT

The inclusion of accelerometer and chip detector sensors should be an integral part of the design process for a new gearbox, though considerable scope exists for retrofit of sensors. The choice for equipment architecture to record and process sensor data consists of two basic options, firstly: a total airborne system which will take data on automatic cue or pilot command, processing results in real time ready for downloading after flight to a compatible maintenance data store. In this case, only flight critical results need to be displayed to the pilot via the centralised warning panel.

The second option is for the minimum sensor fit, with portable equipment to record data periodically for subsequent analysis on the ground.

The first option is the most costly, with processors required for each individual airframe, however this strategy offers the airworthiness benefit of a 'sentinel', able to scan for emerging defects almost continuously. The second option is the cheapest in cost and weight, but offers less security. Given that some health indicators give considerable warning of failure, whilst others do not, the optimum equipment architecture may well be a combination of some real time data processing for in flight results, and a recording capability for off aircraft analysis for the bulk of parameters, which is triggered by certain real time results or on demand. To ease the problem of the volume of data to be recorded for a number of accelerometers and discrete figures of merit (FOM), data compression techniques may be necessary, including the airborne processing of 'snapshots' of raw data into a manageable size, or part analysis eg. producing signal averages. For a complicated gearbox, the full suite of vibration analysis techniques for gears and bearings would need 15-18 Mbytes of raw data storage capacity, which is for the moment beyond an all digital storage medium and this points towards airborne processing of data. A small airborne tape recorder could however be developed to meet this need.

9. MANAGEMENT OF TECHNIQUES

The milestones to be achieved in commissioning an integrated health monitoring system are shown in Figure M. As an example of this approach, the development plan for the EH 101 is shown in Figure N. The essential features are:

a. Development Testing: The definition of algorithms which will be used to determine the health monitoring indicators. An integral part of this is the functional testing of development hardware (sensors and recorders/processors) and the setting of data collection intervals and threshold levels. This may require deliberate fault seeding.

b. Maturity Testing: In the latter stages, the system credibility will be tested prior to certification. The reliabilty of the system, and long term data collecting requirements and in service maintenance interpretation rules will be established.

10. CONCLUSIONS

1. The health monitoring system for a new gearbox should be considered from the design stage and fully integrated into the development programme.

2. There is no universal monitoring technique for the transmission system at present. A matrix of the minimum of cost effective methods will need to be determined covering the likely failure modes.

3. An effective health monitoring system will improve airworthiness and reduce maintenance costs, provided that the data produced by the system is handled and interpreted correctly.

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6. P Gadd, P J Mitchell Condition Monitoring of Helicopter Gearboxes using Automatic Vibration Analysis Techniques. Paper Presented to AGARD Conference Proceedings No. 369 `Gears and Power Transmission Systems for Helicopter and Turboprops.` HMSO London 1984.

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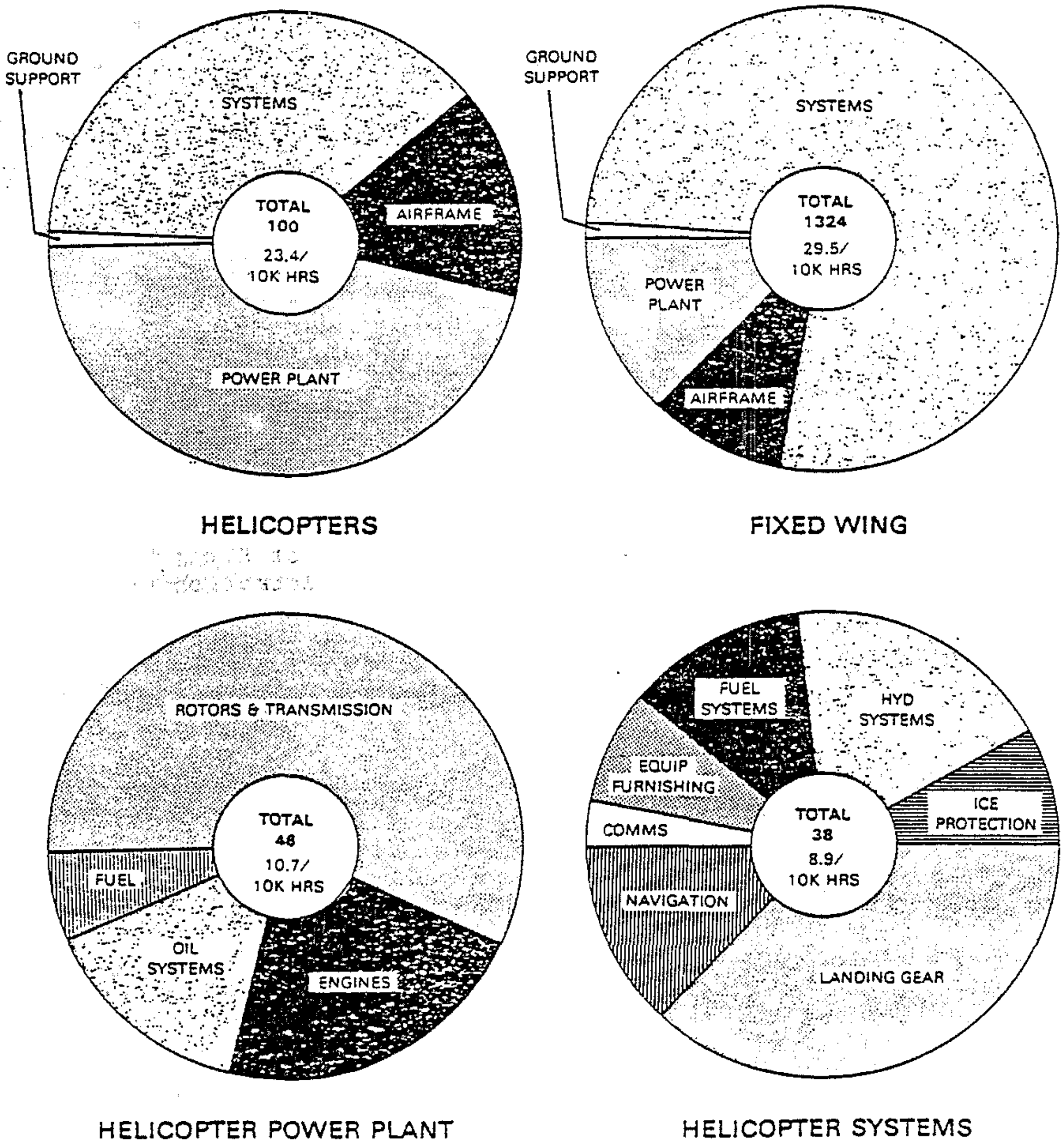
Fig. A

UK REVENUE EARNING AIRCRAFT JANUARY — JUNE 1981

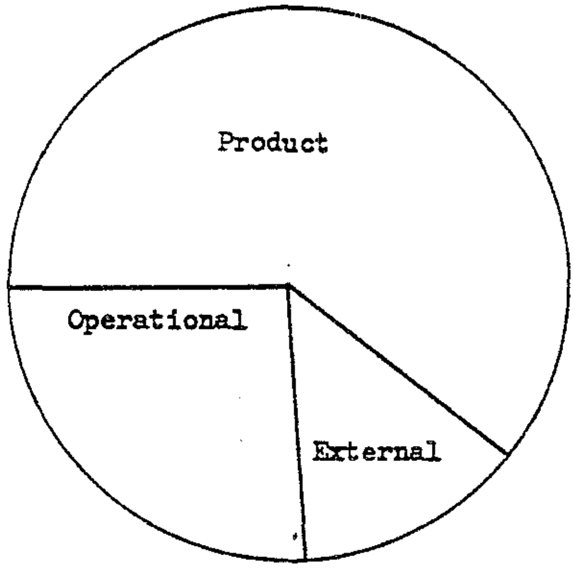


REPORTED AIRWORTHINESS FAILURES

Fig. B

TYPICAL MILITARY HELICOPTER GEARBOX FAILURE MECHANISMS

MAIN ROTOR GEARBOX FAULTS



Product

Design
Assembly
Manufacturing
Materials
Repair Process

Operational

Maintainance Practice
Mishandling in use
Environmental

External

Adjacent machinery
Accessory drive overload

INTERNAL FAILURES

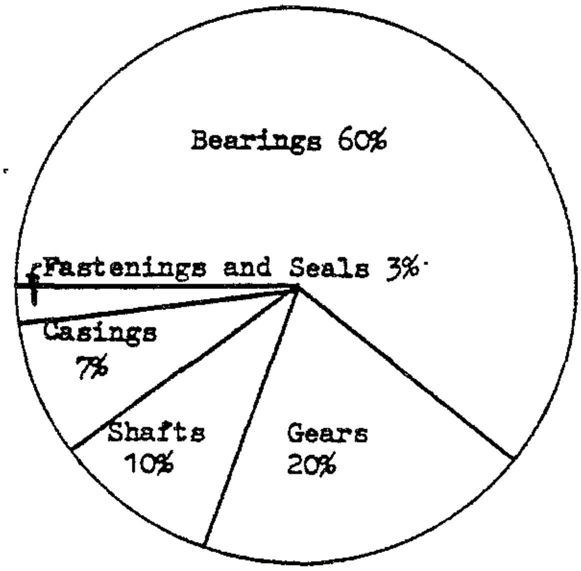


Fig. C

Signal Averaging Process

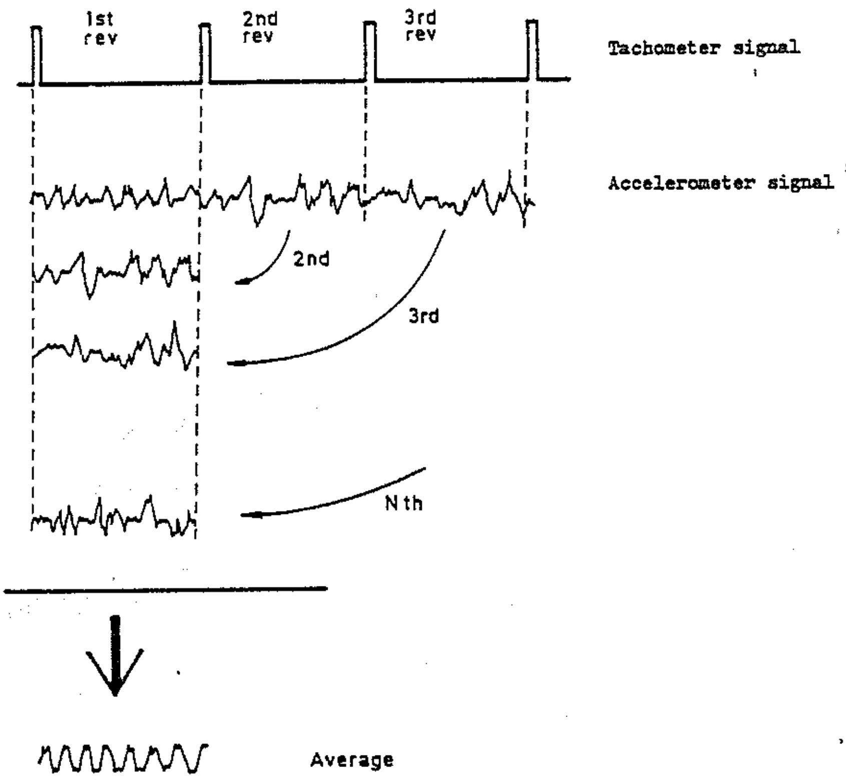
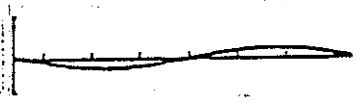
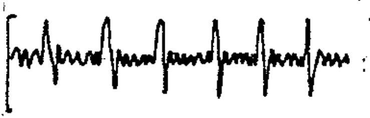
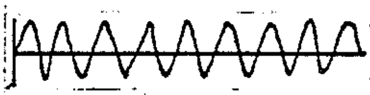
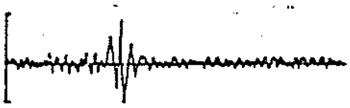
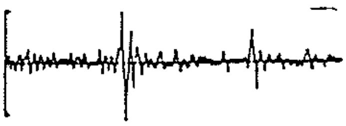
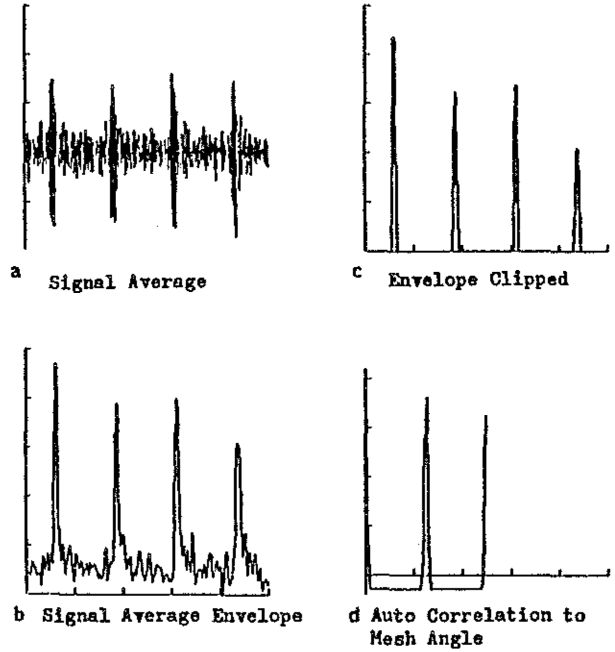


Fig. D

Indicators of Gear Condition

Figure of Merit	Pattern	Indicator	Purpose
FM0		Deviation from a sinusoid	General purpose detector
Balance		Overall modulation	Misalignment Eccentricity Swash Failure of shaft or supporting structure
FM1 A&B		Differences in plant-pass modulation level	Planet load sharing problems
FM2		Correlated impacts	Tooth fracture, chipping
FM3		Sub-harmonic meshing	Parametric excitation Heavy wear
FM4 A&B		A: Single impacts of moderate intensity B: Rise in shaft-order activity	Spalling Tooth fracture Evenly distributed wear
FM 5		Single impacts of low intensity	Early spalling and fatigue cracking



Computation of Figure of Merit FM2B

Fig. G

RAE Farnborough Gearbox Test Rig

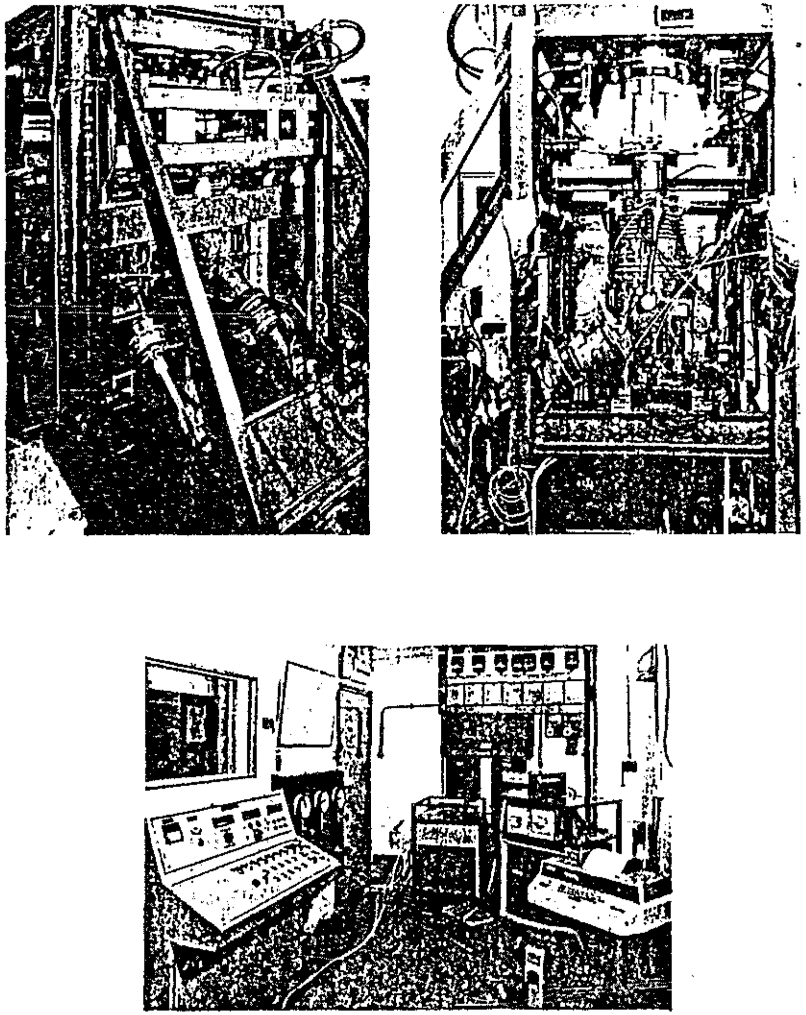
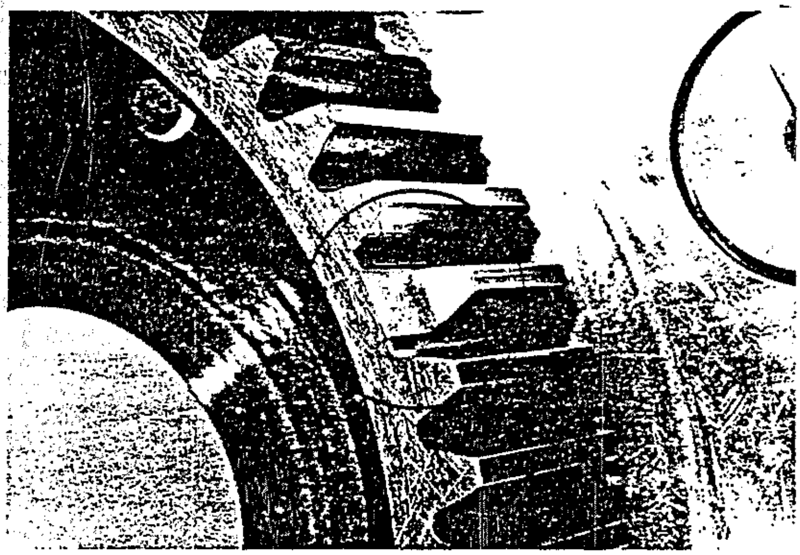


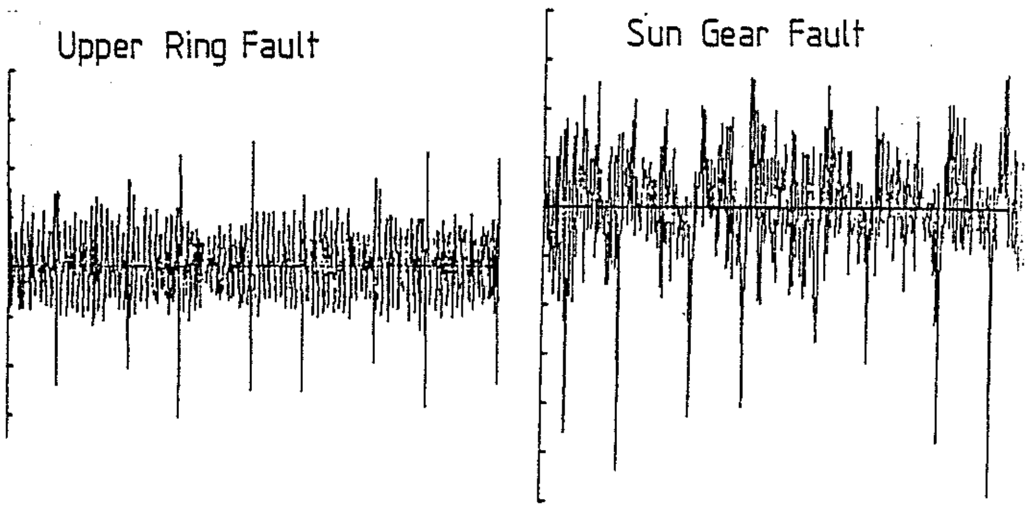
Fig. E

Fig. E



Example of Seeded Gear Damage

Fig. F



Signal Averages of Faulty Gears

TREND CHARACTERISTICS OF VIBRATION PARAMETERS

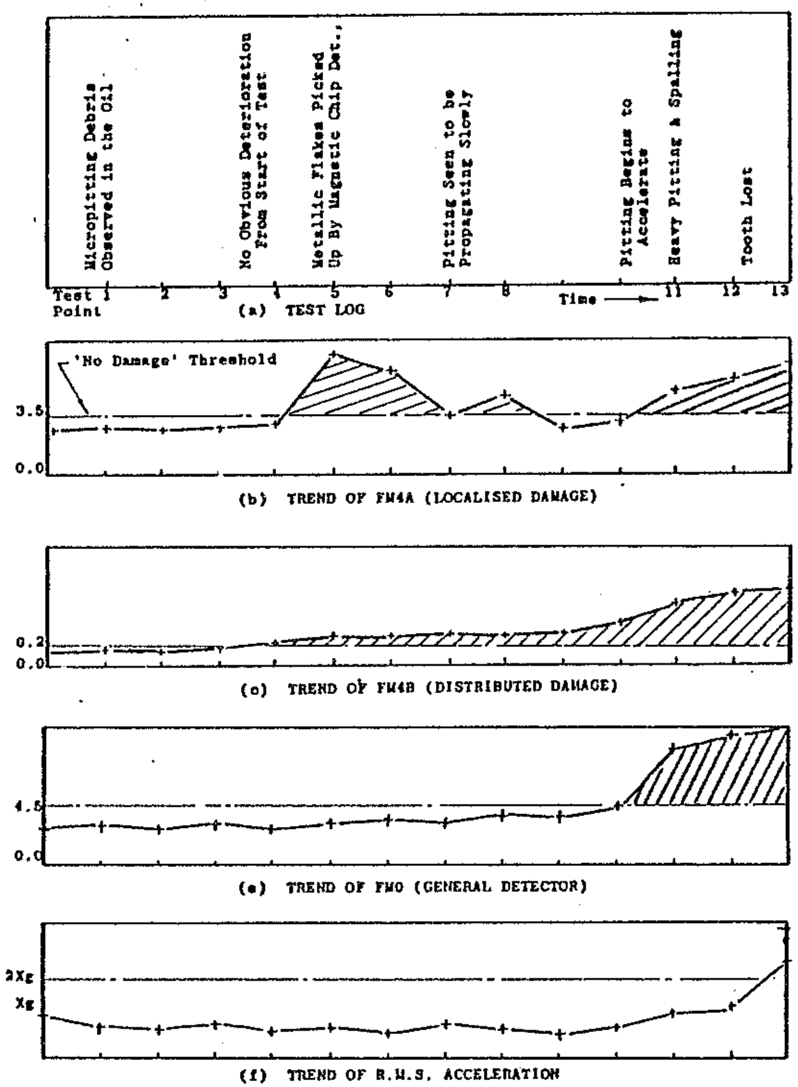
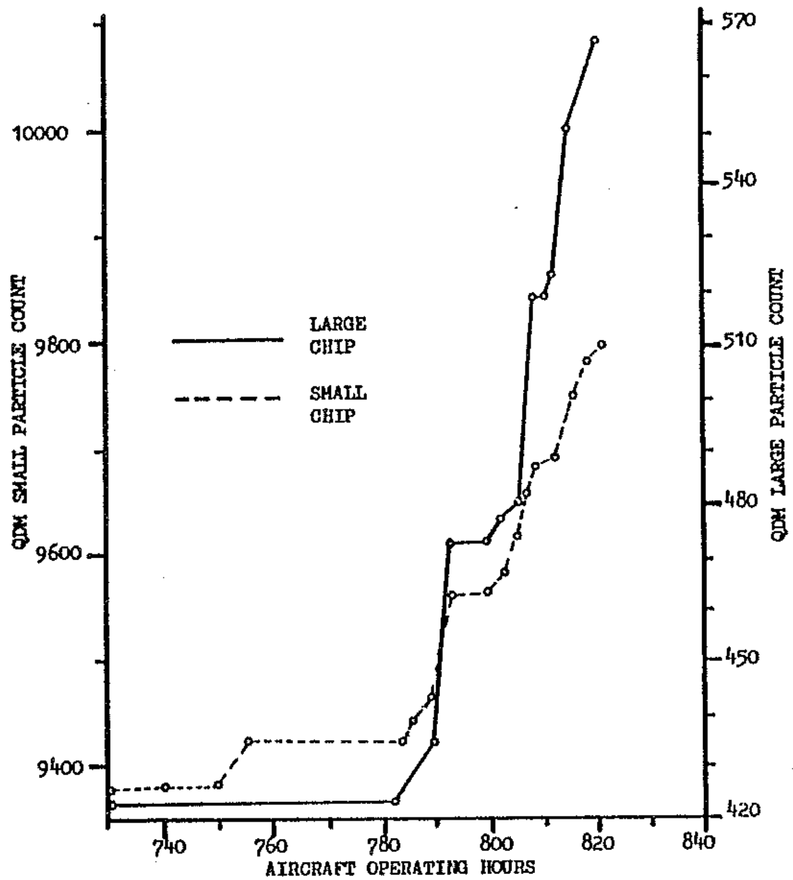


Fig. I



HELICOPTER MAIN GEARBOX
BEARING FAILURE DETECTION
TEDECO QDM SYSTEM

Fig. K

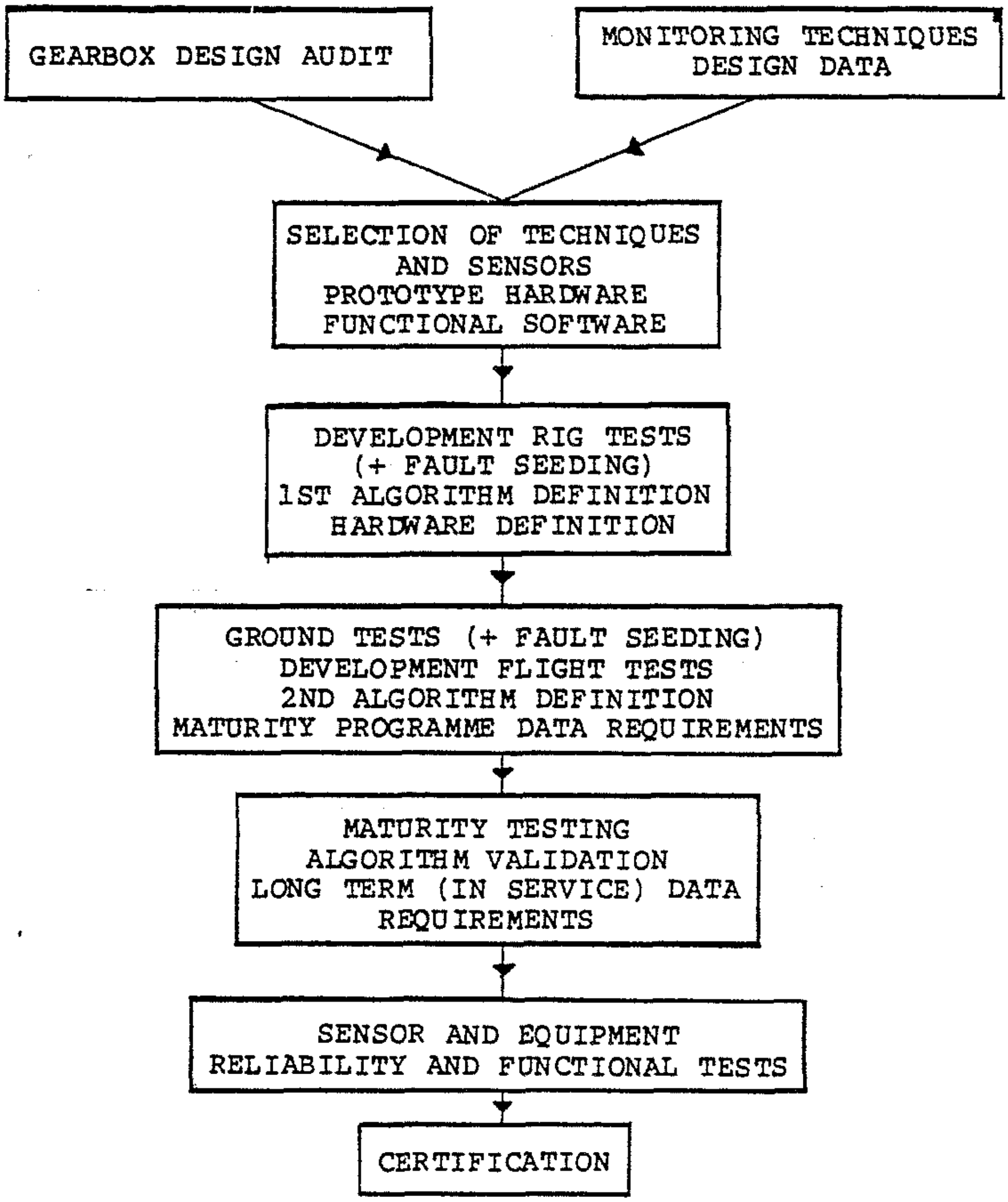
METHOD	ANALYSIS		FAILURE MODE																			
			GEARS									BEARINGS					SHAFTS				
			GENERAL			EPICYCLIC															
						sun		planet		annulus											
			SPALLING	TOOTH CRACK	TOOTH LOSS	TOOTH SPALLING /CRACK	TOOTH LOSS	TOOTH SPALLING /CRACK	TOOTH LOSS	TOOTH SPALLING /CRACK	TOOTH LOSS	EARLY TRACK SPALL	EXTENSIVE TRACK SPALL	ROLLER SPALL	PLAIN BEARING	CAGE BREAKUP	SPLINE WEAR	BALANCE	ECCENTRICITY	SWASH	TORSIONAL RESONANCE
ON LINE FERROUS DEBRIS COUNTER	large chips											✓	✓	✓		✓					
	small chips		✓									✓	✓	✓	✓	✓	✓				
	filter bypass															✓					
VIBRATION	balance																				
	signal average	FM0																			
		FM1A																			
		FM1B																			
		FM2B																			
		FM3																			
		FM4A M6*																			
		FM4B																			
		FM5																			

Fig. J

METHOD	ANALYSIS		FAILURE MODE																		
			GEARS									BEARINGS					SHAFTS				
			GENERAL			EPICYCLIC															
						sun		planet		annulus											
			SPALLING	TOOTH CRACK	TOOTH LOSS	TOOTH SPALLING /CRACK	TOOTH LOSS	TOOTH SPALLING /CRACK	TOOTH LOSS	TOOTH SPALLING /CRACK	TOOTH LOSS	EARLY TRACK SPALL	EXTENSIVE TRACK SPALL	ROLLER SPALL	PLAIN BEARING	CAGE BREAKUP	SPLINE WEAR	BALANCE	ECCENTRICITY	SWASH	TORSIONAL RESONANCE
ON LINE FERROUS DEBRIS COUNTER	large chips											✓	✓	✓		✓					
	small chips		✓									✓	✓	✓	✓	✓	✓				
	filter bypass															✓					
VIBRATION	balance																	✓			
	signal average	FM0			✓																
		FM1A																	✓	✓	✓
		FM1B																			
		FM2B		✓			✓			✓	✓										
		FM3																			
		FM4A M6*	✓	✓	✓			✓	✓												
		FM4B			✓			✓	✓												
		FM5	✓		✓	✓	✓	✓	✓	✓	✓										

Fig. 1

Fig. M


GEARBOX DESIGN AUDIT
MONITORING TECHNIQUES DESIGN DATA
SELECTION OF TECHNIQUES AND SENSORS PROTOTYPE HARDWARE FUNCTIONAL SOFTWARE
DEVELOPMENT RIG TESTS (+ FAULT SEEDING) 1ST ALGORITHM DEFINITION HARDWARE DEFINITION
GROUND TESTS (+ FAULT SEEDING) DEVELOPMENT FLIGHT TESTS 2ND ALGORITHM DEFINITION MATURITY PROGRAMME DATA REQUIREMENTS
MATURITY TESTING ALGORITHM VALIDATION LONG TERM (IN SERVICE) DATA REQUIREMENTS
SENSOR AND EQUIPMENT RELIABILITY AND FUNCTIONAL TESTS
CERTIFICATION

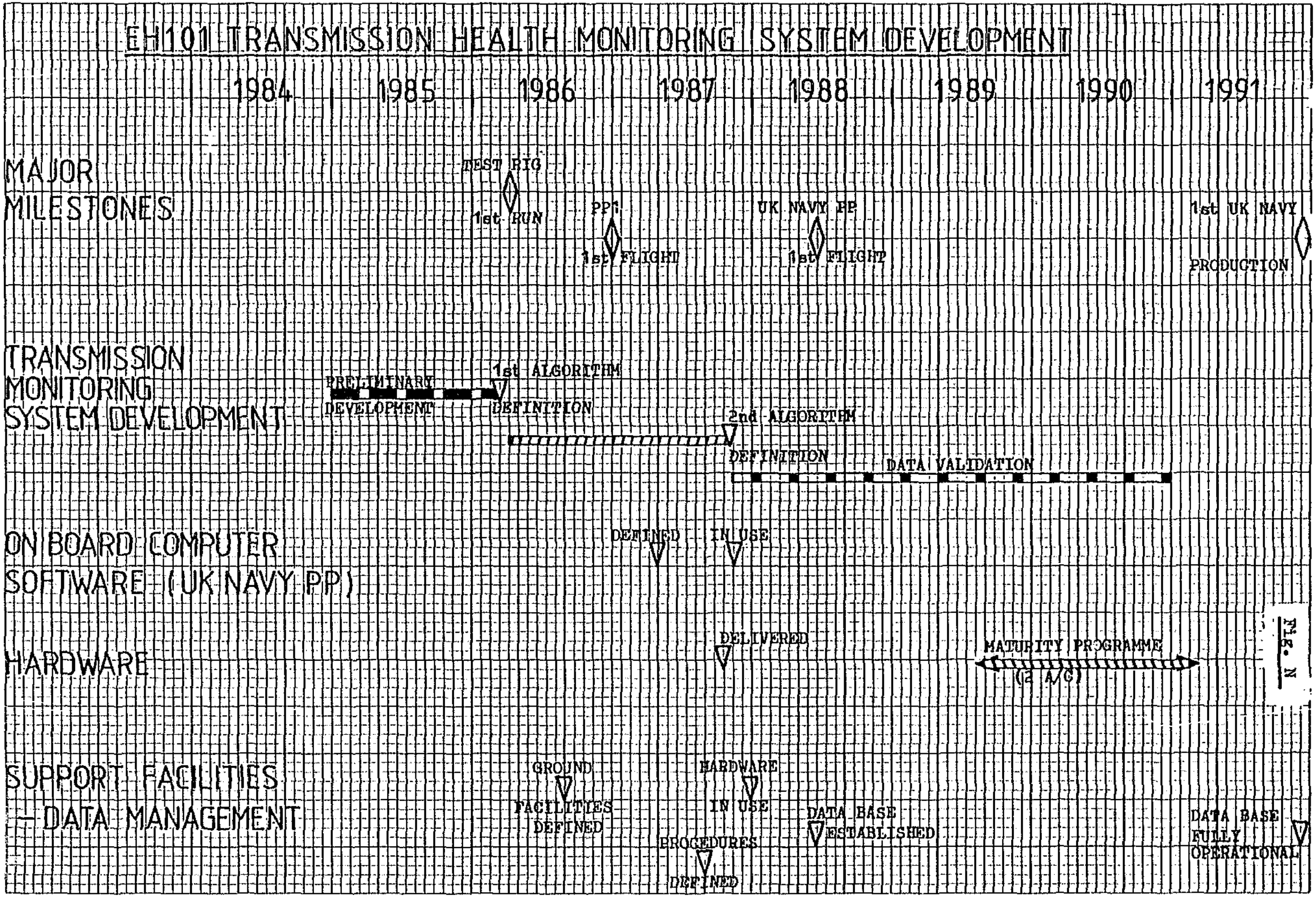

EH101 TRANSMISSION HEALTH MONITORING SYSTEM DEVELOPMENT
1984
1985
1986
1987
1988
1989
1990
1991
MAJOR MILESTONES
TEST RIG 1st RUN
PP1 1st FLIGHT
UK NAVY PP 1st FLIGHT
1st UK NAVY PRODUCTION
TRANSMISSION MONITORING SYSTEM DEVELOPMENT
PRELIMINARY DEVELOPMENT
1st ALGORITHM DEFINITION
2nd ALGORITHM DEFINITION
DATA VALIDATION
ON BOARD COMPUTER SOFTWARE (UK NAVY PP)
DEFINED
IN USE
HARDWARE
DELIVERED
MATURITY PROGRAMME
(2 A/C)
SUPPORT FACILITIES - DATA MANAGEMENT
GROUND FACILITIES DEFINED
HARDWARE IN USE
PROCEDURES DEFINED
DATA BASE ESTABLISHED
DATA BASE FULLY OPERATIONAL

Fig. N