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Marine Gas Turbines - Engine Health Monitoring - New Approaches

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Abstract

Recent developments, coupled with field experience of Engine Health Monitoring Techniques within the Royal Navy Gas Turbine Fleet have enabled a fresh initiative. The advantages of adopting a policy of Condition Based Maintenance rather than a rigid hours concept are outlined and the Engine Health Monitoring (EHM) developments and affects on overhaul facilities are explained.

Introduction

The introduction of marinised Tyne and Olympus gas turbines into RN service in the mid seventies was significant in that new concepts of maintenance and operation were introduced. For the first time, main engines were subjected to upkeep by exchange; the guidelines and policy being similar to the aero world. Monitoring of component life, in service development and ad-hoc methods of engine health monitoring have resulted in the Tyne and Olympus reaching reasonable levels of engine and component life. The emphasis has been to standardise on engine life across the fleet and thereby gain the advantages of simplified overhaul procedures and inspections in the field. Recent electronic developments coupled with a better understanding of our real requirements for Engine Health Monitoring for the gas turbines, have resulted in satisfactory evaluation trials of stand alone units in both industrial and marine installations. These initiatives have enabled us to examine the very attractive advantages to be gained from adopting a policy of condition based maintenance rather than the rigid hours concept. The individual monitoring techniques, shown to be practical in service, are described in this paper together with plans for an integrated EHM system and the known effects on the overhaul facilities.

Visual Methods

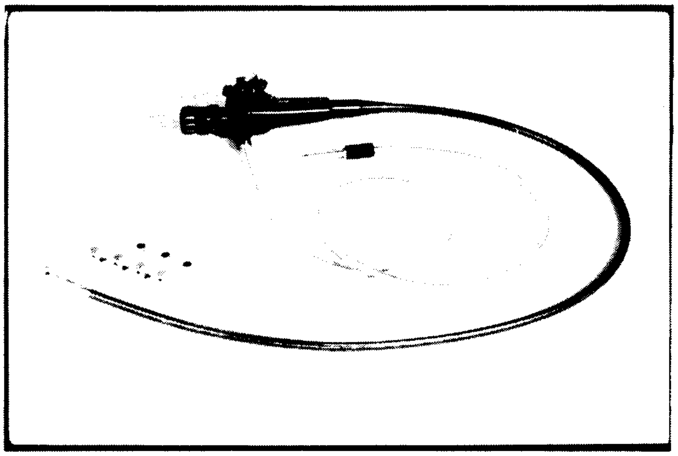

Fig.1 Flexible Endoscope

Even with the most sophisticated data acquisition and diagnostic systems in use, it is obviously advisable, where possible, to carry out visual inspections before confirming a diagnosis. Internal inspection is best achieved using a fully articulated high quality flexible fibrescope (Fig. 1). Although limited by the number of inspection ports on our more mature engines (Olympus and Tyne), it has nevertheless proved practical, to make a good assessment of the hot end of the engine. The use of guide tubes (Fig. 2) in some cases has proved useful to position the tip of the flexible fibrescope close to the area under scrutiny. The scope for this activity is great and indeed this is illustrated by an industrial application, involving a guide tube some 2 metres in length for a power turbine

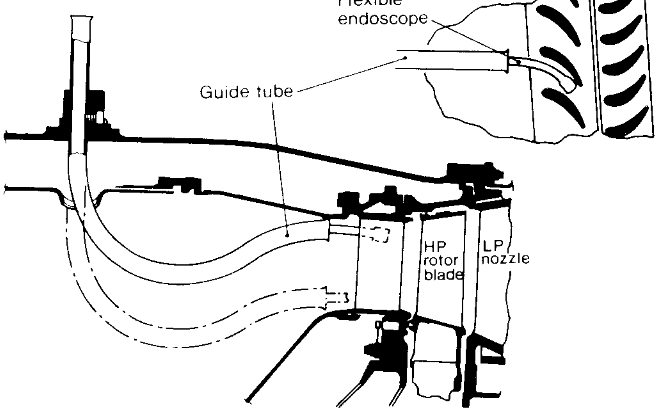

Fig.2 Typical guide tube for flexible endoscope

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inspection. In addition, optical and photographic quality, improved closed circuit television definition and high power light sources have all contributed to the increasing use of this technique with the Royal Navy.

Documentation together with operator training and experience cannot be overrated in importance. Modern optical quality is a two edged sword and too much detail can be as much of a problem as too little. Built in measuring systems assist the operator but there is no substitute for experience in interpretation of the visual image. Diagrams and photographs showing acceptable limits of cracking, buckling, erosion and corrosion are vital. Typical endoscope pictures are shown in Fig. 3. Operator manuals for both the Tyne and Olympus engines have recently been improved in this respect and as operating hours increase, the Spey SM1A book will follow suit. The present users of this information are the Commander-in-Chief Fleet Technical Staff team who perform the inspections on a global basis, but whilst the value of the experience and training of these senior ratings is recognised, it is more cost effective to establish this expertise with the ship's staff; a move that might also serve to dispel the remaining suspicions of black magic which surround the marine gas turbine. The necessary specialist training can now be provided at HMS SULTAN, a shore based establishment, on an ex-development Tyne engine and procurement of flexible fibrescopes for ships is underway. The vulnerability of our existing management system was exposed recently when a special requirement called for an immediate inspection of a particular component, when the only personnel qualified to carry out the inspections were the aforementioned Technical Staff team. A fully trained and sufficiently experienced member of ship's staff with a flexible fibrescope and adequate documentation would have made short work of the inspection and enabled a more rapid assessment of the fleet problem.

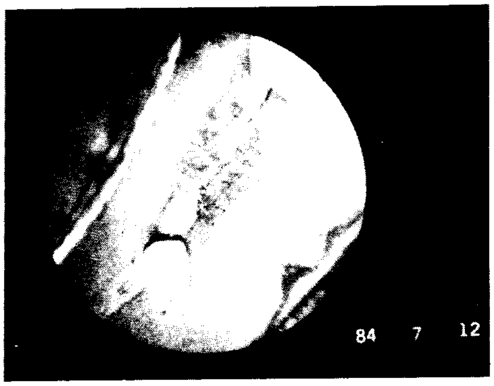

Fig.3a. Tyne RM1C - combustion chamber - cracking between cooling holes from inside the "can"

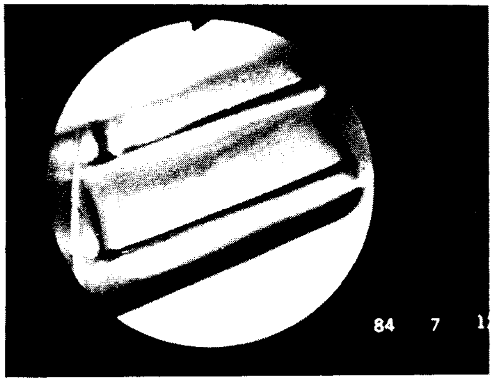

Fig.3b. Tyne RM1C - HP turbine blade - after endoscope has passed through nozzle guide vanes

As previously stated the Tyne and Olympus engines present only a limited scope for visual condition based monitoring and it is not considered prudent to rely entirely on this information for individual engine life assessment. The Spey SM1A engine, to be fitted in T23 and later T22, does however feature a larger number of inspection ports for both the cold (compressor) end and the hot (combustion and turbine) ends of the engine. When the higher powered Spey, namely the SM1C, is developed then even greater endoscope port facilities are envisaged. One should not be carried away by this design feature however as there comes a time when inspection ports provision becomes less cost effective - particularly on the gas turbine "cold end" where Royal Navy experience has shown the simple fixed stator to be a good design point and the achievement of high compressor reliability in service can be partly explained by this feature.

Low Cycle Fatigue Counters

Although gas turbine operators are used to expressing engine and component lives in hours, in practice rotating components are lifed on the basis of major stress cycles. A major stress cycle is experienced by a gas turbine undergoing a transient from stationary to full power and back to rest again. The life of a component can thus be expressed in terms of Low Cycle Fatigue (LCF) cycles. In order that a sensible method of measurement of rotating component life could be made available to operators and overhaul facilities, it was necessary to conjure up a simple though conservative conversion factor to equate Low Cycle Fatigue counts to engine hours run. Thus a record of engine hours alone has enabled a simple although relatively wasteful approach to overhaul and scrap out of rotating components.

In service, the number of major stress cycles accumulated is actually a summation of fractional cycles (a pure major stress cycle is very rare). A series of equations or an algorithm, taking compressor shaft speeds as inputs and outputting a fraction of LCF, is the basis of an LCF counter. A typical LCF profile showing the contribution of part stress cycles is shown in Fig. 4.

Counters are now being deployed in service for two reasons:

a. To improve on the existing conversion factor which is somewhat conservative (a re-assessment based on an updated statistical review is long overdue). Hopefully Olympus and Tyne material costs at overhaul will be substantially reduced.

b. To count individual engine stress cycles in the Spey SM1A application.

The effects of b. are far reaching. For the first time, it will be possible to overhaul each engine on

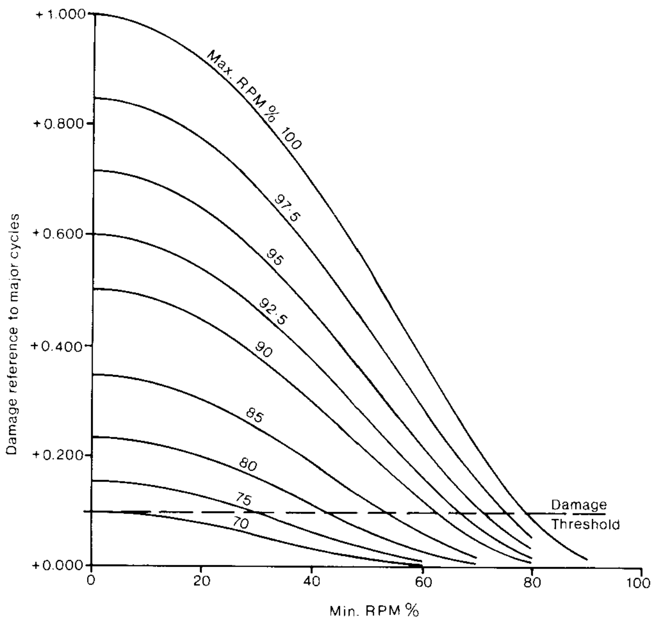

Fig.4 Low cycle fatigue-Typical damage

the basis of actual cycles accumulated rather than a statistical estimate. The effects on the overhaul facilities are discussed later.

Early counters in service feature electro mechanical devices. The advent of the E^2PROM however has enabled a fully electronic device with a safe memory to be developed and in fact it is intended that all the SM1A modules be equipped with such a device. Noise problems, of an electrical nature experienced during trials, have now been successfully surmounted.

Of course not all gas turbine components are lifed on the basis of stress cycles. Ancillary items such as fuel pumps, compressor and turbine blades and many stationary components, where the major factors are frictional wear, erosion and corrosion, are lifed on engine hours or condition upon inspection. It is therefore important to realise that both LCF counts and engine hours are required to be monitored and recorded.

Turbine Life Usage

To take account of those components that are not specifically limited by stress cycles, but which are operating in the arduous conditions of the gas turbine hot end, a turbine life monitor has been developed principally to give some visibility on thermal usage rates. Such a development monitor has been fitted to an industrial engine for over 5000 hours running with good results recording the amount of time the gas turbine operates in various exhaust temperature bands. Factoring this time relative to the design point indicates the accrued effective hours. Real time hours are also recorded for comparison and Fig. 5. shows how the life of a typical turbine is affected by exhaust temperature. At peak operating temperatures, turbine blade creep could be the limiting factor, whereas in other temperature ranges fretting wear, erosion and corrosion will be paramount.

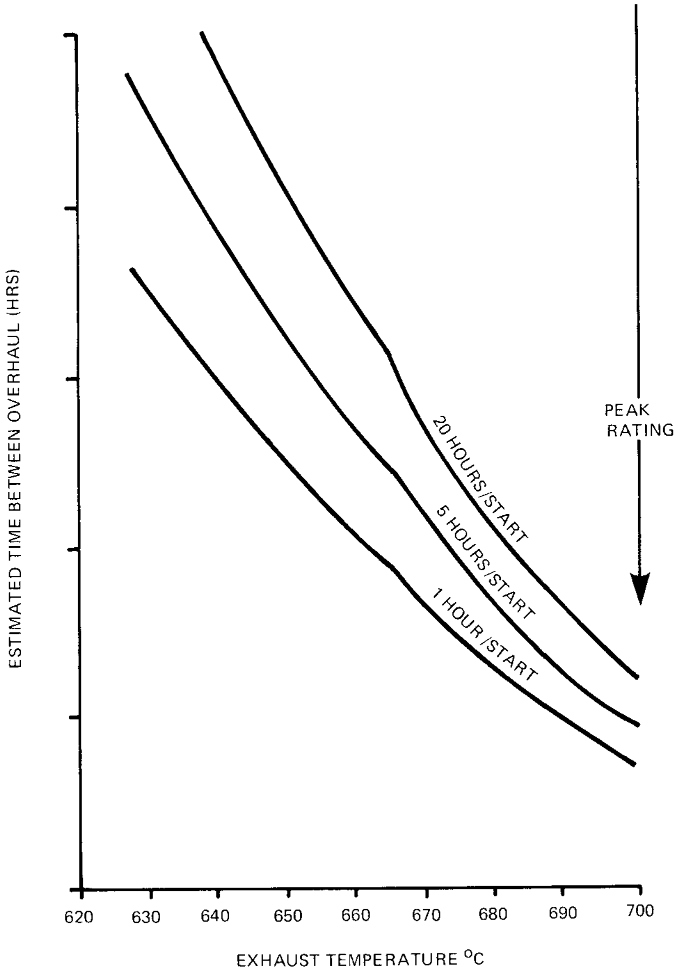

Fig.5 Time between overhauls v exhaust temperature

Initially the effective hours will be determined using the measured exhaust gas mean temperature signal and a simplified theoretical algorithm making assumptions for starting frequency and fuel/air quality. As service experience increases the algorithm may well be refined to correlate thermal usage wear rates, carbon build up and corrosion attack with effective running hours. The empirical life relationships established will be an important consideration when future maintenance is being planned.

The Royal Navy has attempted to gather this data in the past, but it was clear that the technology available at that time, did not allow the necessary reliability to be achieved. For this reason, the use of effective hours was abandoned. Modern electronics however have enabled a new assessment and this technique can now be looked on in a far more favourable light.

The recorded availability of the time at temperature (or overtemperature!) data also gives considerable scope for improved failure analysis in the event of component distress. In the longer term the data will be invaluable in enhancing creep life predictions.

Power Turbine Entry Temperature (PTET) - Spread Monitoring

Experience has shown automatic PTET spread monitoring to be the most cost effective health monitoring parameter on gas turbines with cannular combustion chambers. This is because of the in-service good accessability of the burners and combustion chambers and the costly consequences of ignoring overfuelling or under fuelling on one combustion chamber. Conveniently most gas turbines already have a number of almost symetrically positioned thermocouples in the inter-turbine duct and in the case of marine engines our philosophy has always been to fit triple element thermocouples for self powering purposes.

Development tests on a marine engine with a progressively blocked burner gave very clear results as shown in Fig. 6. The effects of holes in combustion chambers and ducts is not so easily quantified, but the worst scenario - that of a combustion chamber flare off and jamming across the HP nozzles can be seen on PTET spread. The importance of this can only be seen during straingauge tests on turbine blades which often show up as a doubling of turbine blade alternating stresses with a blocked burner and up to a five fold increase for gross HP nozzle blockage. Several in service turbine rotor blade failures have been associated with these types of defect. Development trials and service experience have shown that measurement of individual temperatures at the power turbine entry duct is directly relatable to individual combustion chambers/burners upstream despite the gas turbulence, swirl and distance.

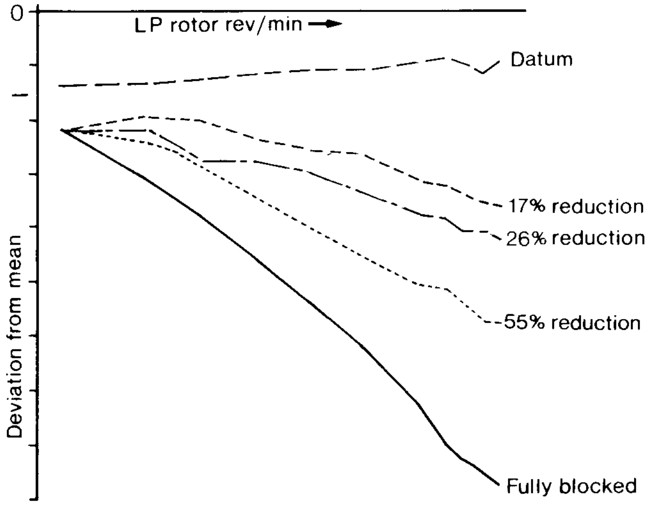

Fig.6 Plot of the effect on exhaust gas temperature spread of progressively reducing one fuel burner main feed (10 burners fitted to this engine)

In-service trials with an automatic spread monitor on a marine Olympus have proved successful in that partially blocked burners were quickly diagnosed and full fleet implementation will take place for Olympus engines. In another application, low power running for long periods by a Tyne engine has shown heavy deposits of carbon on burners at low engine hours. Early diagnosis is obviously important and a simple automatic system is being developed.

Manual monitoring of spread has been shown to be unresponsive, liable to interpretation errors and obviously labour consuming. Automatic monitoring however has potential for further development. Ideas being considered are a replay memory facility and the ability to diagnose faults during start up and accels and decels. Present equipment is confirmed to steady state conditions with a limited alarm memory.

Performance or Aerothermal Assessment

Early trials by the RN using manually plotted graphs were tedious and not successful due to repeatability/accuracy problems and interpretation of parameter shifts.

Although many highly sophisticated automatic aerothermal systems have been trialled in both marine and industrial installations - none have been adopted in RN service.

The primary reasons are the as yet unproven cost effectiveness of a necessarily complex aerothermal system and the regular compressor washing using installed solvent cleaning systems. Identification of the requirement of 'when to compressor wash' is the usual 'sales point' for aerothermal monitoring systems and as an example a Tyne Shore Trials test showed less than 1% performance loss at the end of 3000 hours running compared to the newly installed datum. Service experience with Tyne and Olympus has also shown only a small loss of performance no doubt assisted by their fixed compressor stators and small number of abradable seals.

Failure analysis of the last 5 years Marine Olympus and Tyne removal causes has identified the EHM techniques most likely to succeed in detecting incipient failures illustrated in the following table:

	EHM method	Percentage of all failures
1.	Metal in oil	27%
2.	High oil consumption	14%
3.	Vibration	12%
4.	PTET spread	10%
5.	Exhaust gas debris	10%
6.	Visual	8%
7.	Aerothermal	3%
	TOTAL	84%

As can be seen, aerothermal assessment does not show too well and for this reason, and those briefly discussed above, performance analysis is not likely to figure highly within a near future marine EHM package, although developments in the aero world will be followed closely.

Vibration Monitoring

Rotating compressor and turbine component failures and damage give rise to vibration increases primarily at the fundamental spool frequency, although in certain failure modes such as coupling damage strong twice order frequencies can be sensed. Alarm and trip conditions are set using high and low pass filters to ensure that at high power levels, 1st and 2nd order rotor frequencies are sensed, whilst preventing the low natural frequency of the engine installation and high bracket resonances and blade passing frequencies influencing the output. Automatic trip features which can be overridden for high system integrity situations are particularly important in minimising secondary damage in the event of a component failure.

Future marine developments will see the piezoelectric accelerometer replace the velocity transducer and this has already happened in the industrial application where longer engine lives have identified a wear out problem with high temperature velocity transducers. The accelerometer, which generates a charge proportional to the force exerted on a natural crystal, has no moving components and therefore, will not suffer from this wear problem, thus ensuring good repeatability - an important requirement when monitoring vibration. The output from the accelerometer is converted to velocity units by integrating the signal after first filtering unwanted high frequencies thereby retaining existing alarm and trip levels. Additionally, the sensitivity of future engine vibration systems will be further enhanced by the introduction of rotor tracking. With this facility the vibration levels at the fundamental frequency and second harmonic of each of the engine rotors are automatically monitored by virtue of narrow band pass filters which respond to speed signals from the LP and HP spools. This allows more discriminate warning levels to be set for each spool, leading to earlier warnings, as well as the ability to identify the suspect spool when a problem occurs.

Figure 7 shows the typical response of the fundamental frequencies of a twin spool engine compared to the general level vibration.

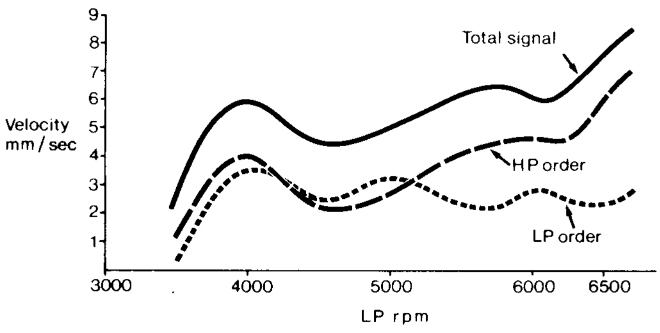

Fig.7 Vibration analysis - typical vibration 1st order tracking

The current tracking system under evaluation has been developed for industrial engines operating over a relatively narrow speed band; the incorporation of a limited automatic signal analyser, to learn and continuously compare the vibration signatures, is ideally required to meet the much broader speed requirements of marine gas turbines. It is anticipated that such a system will be trialled in the near future.

Successful work has been done by the Royal Navy's laboratories to identify imminent bearing and gear distress in service engines. This development work is continuing apace with the trials of a new portable intelligent instrument.

Debris in Oil

Various well documented methods such as SOA (Spectographic Oil Analysis) and Ferrography exist for analysing ferrous particulate carried in the gas generator lubricant, but they have not proved to be convenient techniques for day to day maintenance of a marine gas turbine. These systems rely on regular oil samples and specialist facilities to conduct an analysis - but the worst problem is the time between sampling and analysis.

The concept of Magnetic Chip Detectors (MCD's) which continuosly extract ferrous debris from the gas generator oil as it is scavenged from the bearings and gears has proved to be a quick, simple and successful cost effective approach in detecting incipient failures in Rolls-Royce marine engines. Debris collected regularly on the MCD's is measured using a portable Debris Tester to give a quantitative indication of engine condition and trend plotting the cumulative debris value against engine running time has proven to be very informative of the health of the bearings and gears. A rapid upturn in the trend is usually indicative of bearing or gear distress (Fig. 8.), although of course spurious increases can occur early in the engine life as any manufacturing debris is released. Visual debris analysis backed up by scanning electron microscope examination can easily resolve whether the debris is critical and from which area it was generated.

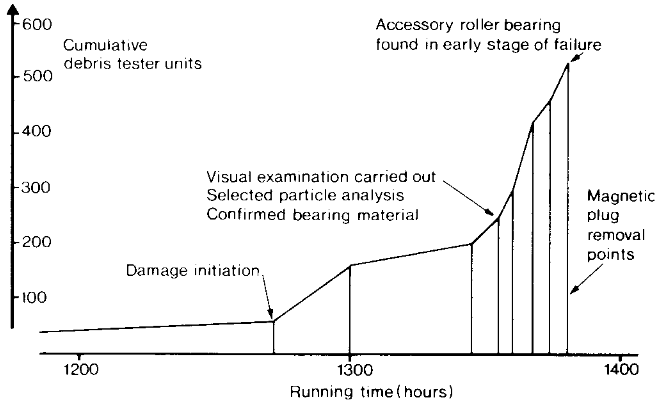

Fig.8 Actual accumulated debris/running time results

It has been recognised, however, that regular inspection of MCD's is labour intensive and this is a 'missing link' for an automatic on-line system because of the importance of this parameter. To this end an automatic chip detector has been undergoing field trials evaluation in Rolls-Royce industrial engines and has recently proved successful in detecting an incipient thrust bearing failure which unusually was monitored over a 2000 hour period of deterioration and on removal still showed only limited fatigue damage.

The automatic chip detector is an inductive device with an internal sensing coil, which produces a signal when debris passes through a magnetic field which is generated around the sensor head. The output is amplified and processed in a signal conditioning unit to provide an indication of debris accumulation by 'small' and 'large' counters. An alarm can be set to detect rate of change or level exceedance. Whilst various other on-line systems have been (and continue to be) evaluated by Rolls-Royce and MOD (PE), this system has been the most encouraging to date.

For future marine applications it is intended to have an automatic sensor in the combined oil scavenge return line to complement the existing MCDs - this is made possible by the relatively low catch efficiency of the MCDs. Inspection of the conventional MCDs will then only be undertaken should an alarm be triggered by this automatic master sensor in order to identify the module affected and to allow debris examination and analysis.

Exhaust Gas Debris Analysis

This process, which is in an early development stage, should not be confused with exhaust gas performance analysis. The process is based on the gathering of debris particles on electronic probes placed in the power turbine exhaust. At time of writing, the full potential of this system is not known but it is hoped that early warning of hot end component disintegration due to erosion, corrosion or impact damage may well be within the equipment's capability. It can be expected that the system will be included as an essential element within an EHM package, if development proves successful.

Marine Engine Monitor - On line

The integration of these separately successful EHM techniques into one package suitable for the Spey marine engine is now underway as a joint venture by the RN and Rolls-Royce plc. The outline of the package is shown in Fig. 9. and comprises:

a. Cyclic Life Counter

b. Turbine Life Factor

c. PTET Spread Monitor

d. Vibration Monitor with Tracking

e. Debris in Oil Monitor

f. Start Up/Run Down Indicator

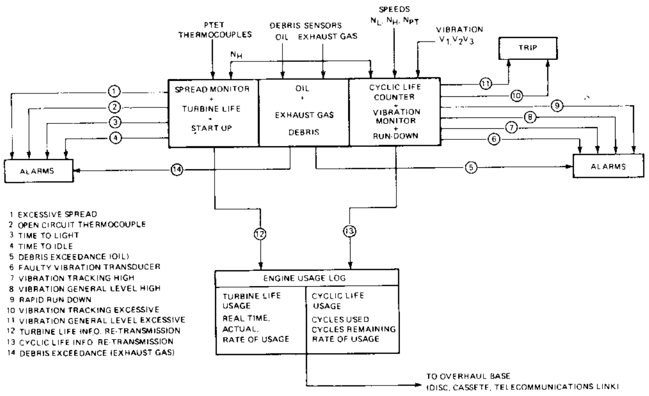

Fig.9 Marine engine monitor on-line

A manual input for lubricating oil consumption and channels for specific requirements such as breather air temperature/scavenge oil temperature will also be available.

Although developed as individual stand alone units, it is clear that some commonisation of signal and function would reduce cost, space and the number of components. Facilities for the transmission of data to the overhaul facilities is also to be incorporated in the design.

Effects on Overhaul

A marine orientated condition based monitoring package must be fully utilised to reap the considerable cost saving opportunities which it presents. Firstly the reduction of the number of catastrophic failures by a credible prognosis will reduce the repair bills considerably as reclaim rather than scrap becomes possible. Secondly, by overhauling engines on the basis of individual condition and LCF accumulated, the savings on spare parts is expected to be not inconsiderable as scrap out rates of expensive turbine discs and shafts should reduce because each will go to nearer its real design life. These advantages will not however be gained without careful planning within our overhaul facilities. For instance an accurate prediction of likely numbers of GTCU's (Gas Turbine Change Units) being returned for overhaul is necessary to provide the necessary trigger for spares ordering. Present estimates use models based on engine hours but, as previously explained, LCF count estimates based on ship operational profile will be necessary in future. With the accent on engine design and overhaul philosophy shifting to a modular concept, engines will be assembled at the workshop using modules from a variety of sources. Indeed there is, in this situation, a clear need to optimise on the turn round times for engine overhauls, the LCF of components and the spares holdings. Thus an overhaul and repair management computer programme becomes essential and is currently being investigated.

Within this system, log books and components life documentation, traditional problem areas in the marine gas turbine world, become even more critical as lifing is done on an individual rather than a statistical average basis. It is the author's opinion however that the advantages of this overhaul philosophy are well worth having and the bullet should be bitten.

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