ENGINE HEALTH MONITORING FOR R.N. GAS TURBINES

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Introduction

Before discussing the various means of engine health monitoring (EHM) used in the Royal Navy for gas turbines, it is important first to answer three questions:

(*a*) What is EHM?

(*b*) Why use EHM?

(*c*) How to apply EHM?

Although almost bound to be subjective, depending on the type of operation of the gas turbine, the following definition of EHM may be assumed in the context of this paper:

> 'Engine health monitoring is the general term for all methods designed to give the operator an indication of a change in condition of systems or components relative to a condition of the particular system or component which is accepted as normal'

The mention of a 'change in condition' correctly indicates that EHM is a comparative method. A single set of readings of engine parameters does not in most cases give a clear understanding of the situation.

The objectives of EHM are:

(*a*) in the short term, to detect developing defects at a sufficiently early stage to prevent or minimize secondary damage;

(*b*) to assess the overall condition of the engine to assist the operator in making his decision when to exchange the engine.

This does not mean that all engine changes should be made 'on condition' instead of after a specified number of running hours. The R.N. believes that, both for operational and logistic reasons, engines must be removed after a certain time even though EHM indicates the condition of the engine to be reasonable. This time is called the declared overhaul life (DOL). Endeavours will be made, however, as experience is gained to make this time as long as possible. In fact, the present defined DOL infers that approximately 20 per cent. of the total number of engines will reach that life. For the other 80 per cent., EHM should serve to ensure their removal before catastrophic failure.

The choice of EHM methods has previously been discussed in an article by Dr. A. V. Cooke, 'Gas Turbine Engine Health Monitoring in R.N. Ships'—*Journal of Naval Engineering*, Vol. 22, No. 2, p.200. Out of a number of basically non-destructive testing methods, the methods that have been adopted are given in TABLE I.

Table I—*Engine health monitoring methods selected for the Royal Navy*

EHM Method	*Area Monitored*
Visual inspection	Outer casings; IGVs; 1st stage compressor blades
Visual inspection via endoscope	Combustion chambers; gas generator turbine blades; inter-turbine duct.
Performance analysis	Compressor blading; turbine blading; combustion chambers; seals.
Vibration analysis	Unbalance of rotating components.
Magnetic chip detectors Filter analysis	All oil-washed components, especially bearings.
Temperature measurement	Plain bearings.
Monitoring during transient conditions (Dynamic data retrieval, DDR)	Bearings; seals; fuel system; starting systems.

EHM Policy for Gas Turbines

Like all engine operators, the Royal Navy will benefit in terms of safety, efficiency, and economy from a well-designed engine health monitoring programme. However, although all means of EHM will in principle be the same as those used by other operators, the R.N. is in a less favourable position in that it cannot make use of sophisticated instruments and laboratories in ships at sea; and, also, personnel on board, although well-trained engineers, are not laboratory technicians. They look at dials and monitor the readings, and should only get alarmed when a certain predetermined danger level is exceeded. At this stage, the warning system ashore (about which more later) has to be triggered resulting in advice back to the ship. Because the danger level is such that, when exceeded, in many cases the engine has to be removed, the ship will be instructed either to make further investigations and report again or to stop further running of the engine.

In the first case, ship's staff gain limited experience of interpreting EHM trends; in the second case, they learn nothing. In both cases, if the engine is indeed removed, ship's staff loose all contact with the engine. A special group of shore-based engineers will remove the engine; it will be sent either to the manufacturer or to Fleetlands, and no feedback about what was found on strip may be sent to the ship.

It is assumed that ship's staff cannot yet be expected to interpret the EHM results they themselves gather. Whether this is a desirable situation is arguable. Although the many associated factors cannot be covered in this short article, some pros and cons are listed because the resolution of this argument, in fact, automatically dictates a great part of the EHM policy that the R.N. should follow.

The greatest advantages of ship's staff doing their own interpretation is that involvement in the procedures and results will stimulate ship's staff to do all they can to assemble relevant information. Furthermore, the availability of trained staff on the spot, especially in the middle of the ocean, is a valuable asset.

The greatest disadvantage is the cost of training people to such a level that they can be expected to make the right deductions. As no extra complement can be allowed, these people must come from existing ship's staff, thus calling for a considerable amount of their already heavily loaded training programme having to be devoted to EHM.

The present situation is, therefore, not to expect ship's staff to do their own interpretation of trends. In part, this policy is due to the cost and space requirements of the instruments and equipment which would need to be carried on board. In addition, current engines have very limited inbuilt EHM data collecting facilities.

For several reasons, a firm EHM programme is still not off the ground, and the R.N. is now in a position where, being a potentially important operator of gas turbines, it is lagging behind some operators in actual knowledge about the operational side of EHM. Also, as the number of engines in service has increased considerably and is still increasing, retrospective fitting of new instruments is getting more expensive all the time.

EHM Methods

In the following, the past, present, and anticipated future of the various ways of engine health monitoring are discussed.

Endoscope

An endoscope was issued to ships for general purposes some time ago. With the introduction of gas turbines, the first reaction was that this endoscope should also be used for these engines. Some adaptation of this standard endoscope set was, however, necessary.

The number of inspection holes to be provided was agreed upon by the MOD and the manufacturer, and until now this rigid endoscope has performed well for the purposes for which it was designed. Periodic inspections are now prescribed to inspect the hot end of the engine. However, only half the combustion chambers can be inspected in one of the main gas turbines, while also the high-pressure nozzle guide vanes and high-pressure turbine blades can only be seen from some considerable distance.

As modification of this engine to allow inspection of all combustion chambers would be a very costly job, it was recently decided that a flexible endoscope should be provided as an addition to the existing rigid set. This decision was taken despite the fact that flexible endoscopes still have considerable disadvantages, the most important being:

(*a*) price;

(*b*) liability to damage;

(*c*) difficulty of orientation while looking through it.

The last is especially important. One really needs to be an expert on the engine to recognize the parts at which one is looking. However, the engine manufacturer has designed some tubes that can be inserted through the endoscope holes and through which the fibroscope can be guided to the most important parts to be inspected. All other additional possible observations are seen as a bonus.

Although, of course, thoughts have gone to using a TV camera, it was decided, at least for the time being, not to issue these for service on board as not being cost effective.

If, in the future, a Gas Turbine Inspection Group (discussed later) is formed, it is most likely that such a group would use one of these fibroscopes provided, of course, that the probe can pass through the holes available.

It is felt that perhaps too little attention is paid to endoscopes. It is a simple, reliable device that helps the operator to find defects—firstly, as a primary means of detection and, secondly, as the follow-up inspection after a defect has been detected or is suspected via other means. For this reason, in future design engines ample endoscope holes should be provided to allow easy inspection of the main parts of the engine. This should preferably be via rigid endoscopes as it is felt that definition and orientation are best, particularly for untrained operators.

A simple engineering rule can be applied to endoscopes: seeing is believing!

Chip Detectors

The gas generators in use in the R.N. are fitted with magnetic chip detectors in the scavenge oil lines. In its simplest form a magnetic chip detector is a magnet inserted in an oil pipe, catching magnetic pieces of metal that pass through the pipe.

At the time when these engines were designed, little attention was paid to this form of EHM and almost as an after thought the plugs were included in the system. Subsequently it was found that a magnetic plug has a low catch efficiency (total amount caught by the plug divided by the total amount of metal flowing through the pipe times 100 per cent.).

By just inserting the plug at the most convenient but not necessarily the best place, catch efficiencies as low as one per cent. were experienced. It is clear that these low efficiencies do not allow sensible monitoring, and effort is now being put into developing a system to increase the catch efficiency. Recently, very good results have been obtained by the engine manufacturer with a vortex chamber where practically all dirt (magnetic and non-magnetic) assembles. Hopefully this design will be incorporated in future marine engines.

These magnetic plugs are not intended as a filter; they are put in the system to indicate whether abnormal wear is occurring. When examining a contaminated plug, two questions have to be answered:

(*a*) Is the amount of metal abnormally high?

(*b*) If so, can the engine component that produces this metal be identified?

Until now the first question has been answered completely at the discretion of the inspector. He does this by visually comparing the amount of debris with that which he has seen on previous occasions; guidance in doing so, however, has been minimal.

To make quantitative assessment of the debris more precise, a debris tester that presents the operator with a dial reading representative of the amount of metal found on the plug is being evaluated in two ships. By plotting these readings cumulatively, a curve is created the slope of which is a measure of the rate of wear of the engine parts being monitored by the relevant chip detector. A sudden change in slope indicates an abnormal happening in the engine. The first results have now been received and look promising, so steps have been taken to supply each gas turbine ship with a debris tester.

However, a high quantitative assessment is not the only indication of a developing defect: recently, an impending failure was indicated by only a few chips. It is necessary also to make a qualitative assessment to decide from what kind of engine part the chip originated. Obviously here a more detailed knowledge of the engine is required. A handbook has recently been written to explain and describe the various forms of chips that have been found on chip detectors. It is hoped that this will simplify the detection of the type of engine part affected, thereby making possible a better assessment of the danger to the engine. This handbook is to be issued in the form of a BR in the near future.

Experience with chip detectors in the R.N. is very limited. This is mainly because engines that have failed did not do so in a mode detectable by chip detectors. In two cases where chips were found, the behaviour was such that no established therory could be applied.

As a variant of the magnetic chip detectors, remote particle detectors have now been put on the market by several manufacturers. This is a device which counts the number of particles passing through it or collected by it and transforms this count into an analogue or digital read-out. Some operators, especially of aircraft, seem to be interested, although others claim that a cockpit read-out might urge the pilot to take unnecessary emergency action. Unfortunately every detector has its own disadvantages.

Up to the present, the conventional chip detector seems to have performed reasonably well, and it can be inspected daily by engineers who are always available anyway whether there is a remote counter or not.

For this and other reasons, it is felt that improving the catch efficiency of magnetic detectors should have priority over remote particle detectors. It is therefore not expected that remote particle detectors will be used in the R.N. in the foreseeable future unless a device becomes available that indeed presents great advantages.

Spectrometric Oil Analysis

Spectrometric oil analysis (SOA) is, at least at the present time, a rather controversial part of EHM. Strongly recommended by some, condemned by others, but watched with interest by practically all engine operators.

To perform an analysis a sample of lubricating oil is taken which is then sent to a laboratory where it is examined using techniques like atomic absorption, atomic emission, X-ray fluorescence, or neutron activation.

A SOA programme (SOAP) was discussed in the Royal Navy as early as 1966. However, after some time, it was decided that SOAP in R.N. ships could not be justified for a variety of reasons, the main ones being:

(*a*) The turn round time for an oil sample is far too long.

(*b*) The lub. oil content of a marine gas turbine is large, and very low p.p.m. numbers for metals in the oil can indicate an impending oil failure. It was thought that instruments would not be accurate enough to inspire sufficient confidence on which to base a decision whether to run the engine on or to stop it.

However, H.M.S. *Amazon* and H.M.S. *Sheffield* were supplied with equipment for taking samples for forwarding to the Admiralty Oil Laboratory. The purpose of this was to relate engine condition in ships to the lubricating oil sample at a particular time. This is clearly not, in the first place, for the prevention of defects developing fully undetected but more as an insurance policy. Perhaps SOA will be used after all.

As far as the building up of experience is concerned, there is a strong parallel between SOA and magnetic chip detectors. Only one failure has occurred to date of the type that should cause an increase in Fe p.p.m. reading, and indeed it did. Well in advance of the final breakdown of the relevant part, a Fe content of between 4 and 5 p.p.m. was measured in an Olympus. This more or less contradicts the assumption made earlier that we are looking for very low p.p.m. numbers. Furthermore, the Naval Aircraft Materials Laboratory have found a defective bearing in one of British Steel's large mills with an enormous capacity lub. oil system.

Of course, the length of turn-round time is still a very valid argument. However, as so many operators are interested in SOA, a lot of investigation is taking place and it would not be at all surprising if an instrument was soon to be manufactured at an acceptable price that could be issued to each ship capable of giving the operator a reliable reading.

The SOA programme at present running in the Royal Navy should therefore be continued, not the least because the number of engines involved is so small that:

(*a*) the effort put into the programme is not very great;
(*b*) for a defect to occur in a relatively short period of the type that should be shown up by SOA, a considerable number of running hours per engine is necessary.

It must be said however, that, unless a cheap instrument can be produced, the SOAP will not be extended to other ships, except as confirmation of an impending defect which has already been indicated by other EHM means, or to confirm findings which can only be done by using the experience so far built up by the present SOA programme.

SOA is not intended to be a replacement for magnetic chip detectors or remote particle detectors; different ranges of particle size are measured by each method which must therefore be considered as complementary.

Vibration

It hardly needs any explanation to understand why vibration detection and analysis is an important method of EHM for gas turbines. Not only does the method detect failures, some developing, some already complete, but also analysis will tell with a high degree of certainty which rotating part is causing the vibration.

No doubt chemists will argue among each other about which is the best method of spectrometric oil analysis. Vibration however is an engineers' problem and therefore all arguments take place 'in house' about what method to use, what units to use, and how to interpret the results.

It is not within the scope of this article to discuss all possibilities. The method used on the modern gas turbine in ships is a very simple one, and does not burden ship's staff with too much information. Each module has two vibration pick-ups (velocity transducers), one for the gas generator and one for the power turbine.

The signal is integrated to give an amplitude reading. No doubt, in the past, arguments have taken place whether this amplitude should be presented as peak to peak, RMS, average, or real peak; at any rate the choice was peak to peak. For each transducer the maximum allowable value is given and if this value is exceeded certain predetermined actions must be taken.

Simple and perhaps inaccurate as the method may be, it has helped in several instances to detect, although not to identify, a vibration problem. For identification, more sophisticated procedures and instrumentation have to be used. At present, equipment is manufactured which is easy to operate and with which the operators can perform a vibration analysis and thus identify the problem themselves and by doing so make their own decision whether to run on or stop the engine, or they can signal the results to a shore establishment so gaining time for preparations for repair or for engine change.

As a vibration analyser is already held on board for other equipment and the adaptation of the vibration monitor to accept such an analyser could be done at low cost, it is thought by the Royal Navy that this could well be a cost effective investment.

Also, a system is being developed to display average velocity instead of amplitude. Again, of course, it can be argued whether this is the right way to display the velocity but, as the engine manufacturer is of the opinion that it is and as the exercise was initiated to reduce the cost of the equipment by standardizing on average velocity for all engines, the R.N. has accepted the recommendations and is, in fact, sponsoring trials to optimize the new equipment for the engines in use in the modern warships.

The advantage of velocity over amplitude is mainly that the limit for velocity is approximately the same for the complete engine running range while the limit for amplitude and also for acceleration is dependent on engine speed. Besides, the British Standard recommends velocity display as the parameter for engine vibration, although it recommends the display to be RMS value. The engine manufacturer, however, still prefers the average value to be displayed mainly for historical reasons.

A sudden high change in the measured parameter will most likely be detected almost immediately. Whether in that case extensive secondary damage can be prevented by rapidly shutting down the engine is completely dependent on the kind of failure occurring. However, slowly developing defects which may well be of the same importance are more difficult to detect at first glance and therefore vibration readings should be plotted over the whole power range. The operator should assume a defect is developing immediately a predetermined difference occurs between the reading and the data established on installation of the engine, and he should then start further investigations.

Performance Analysis (Gas Path Analysis)

The name of this part of EHM implies that by measuring certain parameters the condition of the gas path can be analysed. This, indeed is what the Royal Navy hopes in the end it will achieve. The procedure is as follows: on installation of the engine, it is run at not less than five power levels in the band 65 per cent. to 85 per cent. of full power. The engine must be run for a minimum of ten minutes at each power level to achieve stable conditions. At the end of the stabilizing time, the following nine parameters are recorded:

Ambient temperature
Ambient pressure
Turbine entry temperature
L.P. compressor speed
H.P. compressor speed
Main shaft power
Compressor delivery pressure
L.P. turbine exhaust pressure
Fuel flow

L.P. turbine exhaust pressure over ambient pressure gives the engine pressure ratio (EPR) against which the other parameters are plotted. EPR is chosen as this parameter is believed to be the best representative for engine power. For the time being, however, we have to stick to L.P. compressor speed as turbine exit pressure tappings are not yet available.

In order to be able to compare the parameters with those previously taken, the values have to be corrected to standard ambient conditions. The percentage change from the data should then be plotted. The curves thus produced will show trends when the gas path deteriorates.

However, here is where the first problem occurs: What does the trend mean? For most individual defects, it is not too difficult to predict which parameters will be affected, but a combination of defects may present a very difficult interpretation problem.

Two things are becoming absolutely clear: firstly, a lot of information has to be assembled from trend curves and inspections on overhaul to be able to correlate the trends with defects; secondly, by manually plotting, inaccuracies are introduced that make it practically impossible to detect an engine deterioration of less than about 10 per cent. in power. The accuracy of these methods is also not helped by the instrumentation at present in use in the Royal Navy.

At this stage two questions have to be answered:

(*a*) Is it cost effective to invest in an instrument that is directly fed with engine parameters and that, after the necessary calculations, produces the percentage deterioration?

(*b*) As development and introduction into the fleet of such an instrument will take quite some time, must operators go on plotting manually?

It would be better to deal with the second question first. Some time ago ships were instructed to embark on this manual plotting programme. The impression is that:

(*a*) it is a time consuming procedure;
(*b*) the programme could not be sufficiently justified because of lack of experience. Hardly any results from trend plotting have yet been received.

The programme has therefore arrived in a vicious circle that is very difficult to break.

However, engines are now being returned from the fleet for overhaul or the incorporation of essential modifications. When these engines arrive at the overhaul facility, the performance is measured and it has been found that up to 34 per cent. of power was lost without linking this loss to gas path deterioration. It is felt that however inaccurate the ships' instrumentation may be and whatever inaccuracy is introduced by manual plotting of the curves deterioration of this level must be detected also by manual plotting.

This brings us to the first question which in the light of the above is not too difficult to answer. When it is worked out what savings in fuel consumption could be realized by performance monitoring, it is quite clear that we can afford to invest a reasonable amount of money and still be sure that an instrument will pay for itself before long. The danger is that too much is expected from such an instrument. It must be realized that the only useful things it will tell us are:

(*a*) that the compressor is dirty;
(*b*) that the combustion is inefficient;
(*c*) that the turbine is heavily corroded or eroded or both;
(*d*) that variable-geometry or bleed valves are not operating properly.

For all other defects, other means of EHM are probably more efficient.

Dynamic Data Retrieval

Much of what has been said about performance monitoring can also be said about dynamic data retrieval (DDR). Several engine parameters can be fed into a recorder which will then produce an analogue plot of the parameters against time. Under transient conditions these plots will show any abnormalities when compared with those from a healthy engine. This is no doubt a very valuable tool for setting up engine controls and checking them afterwards.

Part of the DDR system will be a tape recorder on which preselected parameters are constantly monitored so, in the case of an engine failure, the behaviour of these parameters during the preceeding ten minutes can be 'played' back.

Again, interpretation of the plots is the problem. Although some abnormalities can be explained or analysed theoretically, many others can only be interpreted after long experience. And again, any investment in this area could well prove to be cost effective in future, the more so because DDR can be used for other purposes than EHM. Experience with DDR for EHM is very limited indeed.

Conclusions

From the foregoing, it is clear that experience with EHM on gas turbines in the Royal Navy is very limited. At least two things may have contributed to this: firstly, EHM involves quite a lot of time and paperwork for ships' staffs already burdened with a lot of administrative work, and it may be thought that EHM adds an unacceptable amount of extra work—an opinion greatly influenced, of course, by the fact that no direct solutions can be given to problems. Again the vicious circle! Secondly, feedback of inspection results obtained by overhaul facilities has not yet reached its optimum. An organization could well be set up that concerns itself entirely with gas turbine defect investigation.

On board ships, possibly quite a lot of information is lost because inspections are done by relatively inexperienced personnel who are often moved around.

thus any experience gained may be lost. The Royal Navy would gain enormously from the experience of a special group of gas turbine inspectors—people who will have seen and inspected many more engines than any member of a ship's staff.

Another aspect to be investigated is the interpretation of EHM results. Again, all results should be sent to one co-ordinating body in which an enormous amount of experience would be built up over a period.

Only by doing these things can a well-running EHM organization be expected. It must be noted that feedback and adjustment of procedures are the key to successful operation of gas turbine engine health monitoring. Both are at the present taking place on an *ad hoc* basis only when time and availability of personnel allow.

Although an appreciable amount of effort is put into the development of new EHM(NDT) methods, it is felt that more co-ordination is needed to prevent overlapping of the efforts of the various individuals responsible for other naval machinery.

For gas turbines, rather than tasking any existing R.N. organization with the addition of EHM to their work package, a new group (perhaps to be called the Gas Turbine Inspectorate) should be formed to give its undivided attention to the subject. This would not only take over the work at present done by the manufacturer's service department but also use their experience to interpret EHM trend plots. The group should be in close touch with overhaul facilities to get first-hand feedback. It is also clear that continuity of personnel is important, at least in this learning period.

It must be realized that now that the gas turbine fleet is growing so also must the Royal Navy's understanding of EHM trends grow. If this does not take place, the most economic operation of gas turbines cannot be guaranteed.

The views expressed in this article are those of the author and do not necessarily represent those of the Ministry of Defence in which the author recently spent an Exchange Service appointment.