GAS TURBINE ENGINE PERFORMANCE MONITORING

DEVELOPMENT OF A LOW-COST SYSTEM FOR USE ONBOARD NAVAL VESSELS

BY

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Introduction

Potential methods for engine health monitoring (EHM) on board naval vessels were outlined in 1975 by Cooke[1]. These included visual inspection, vibration analysis, performance analysis, spectrometric oil analysis (SOA), temperature measurement, and monitoring during transient conditions. SOA was considered to be a proven technique but not cost effective for on-board use. Other methods, where the necessary expertise and the costs are high and the possible gains small (e.g. ultrasonics), were rejected. Cooke concluded that performance monitoring using existing ship's instrumentation should be capable of detecting engine deterioration or in-service damage. It seems, however, that performance monitoring has not had any great success to date; this is probably due to the extra work load imposed on the engineering staff, combined with the fact that deterioration in service is not large. With the advant of programmable calculators, the performance calculations required for trend analysis can be carried out with minimal additional work load, permitting the Marine Engineer Officer (MEO) to keep close track of engine performance and detect any failures at an early stage. When used in conjunction with the other available methods for EHM, an effective and low-cost system should result.

Requirement for System

Previous work by one of the authors[2,3] has clearly demonstrated that an individual system must be tailored to the needs of the specific user. Large users, such as major airlines, have access to major computing facilities and operate large numbers of engines, and systems such as AIDs (Airborne Integrated Data Systems) are in use; these systems are expensive and there are controversial views on their cost effectiveness. Gas pipelines operate significant numbers of gas turbines, with major pumping stations operating several units frequently of more than one type; such stations may have computers already available for station control and fuel optimization, and a fairly sophisticated analysis package may be developed using the existing computing capacity[2]. At the other extreme an extremely simple system using a programmable calculator, existing engine instrumentation, and manual data logging was developed for use with a single Air Cushion Vehicle[3]; a system of this sort is obviously limited in scope but has proved very successful in use and was provided at negligible cost.

Although major navies such as the Royal Navy, the Royal Netherlands Navy and the United States Navy are large users of gas turbines, it should be realized that each individual ship at sea is much more akin to a small user such as the ACV operator mentioned above. The MEO will have responsibility for up to four engines of two different types in the R.N. and R.Nl.N. and will be forced to make decisions on engine condition largely in isolation when at sea. The aims of the EHM system described in this paper are to provide a simple method for carrying out performance analysis at sea, to assist the MEO in making a more informed judgement on engine condition. Trends of important parameters can readily be produced and the system, despite its simplicity, offers some diagnostic capability.

In order to win acceptance by the user, the system must meet the following requirements:

(*a*) *No Increase in Work Load*—The engineering staff are not going to be interested in any system that increases their already high work load. The system developed is based on the readings currently logged on board and presents data for trend analysis very rapidly. If required, trends could be produced on a daily basis but this would probably not be necessary in practice; it is a simple matter, however, for the MEO to check engine condition on a daily basis.

(*b*) *Credibility*—The system developed must be understandable to normally qualified marine engineers; while esoteric systems may be viable in some markets, they are clearly not suitable for shipboard use. The system developed here is merely a mechanization of the calculations which should normally be carried out to correct for changes in ambient condition and comparison with a baseline.

(*c*) *Use of Existing Instrumentation*—The instrumentation used on most naval installations is primarily concerned with safe operation rather than performance monitoring. The basic aim is to provide the watch-keeper with a visual picture of engine operating conditions. Instrumentation displayed in the ship control centre (SCC) is normally restricted to shaft speeds and turbine temperature. Other signals such as pressures, fuel flow, and power may be available but not continuously measured. Clearly, to be cost effective, use must be made of the existing instrumentation; once the user has gained confidence in the system he may wish to extend the instrumentation, but this is the user's prerogative. The installation of extra instrumentation can be both troublesome and expensive, and the over-instrumentation of an engine can result in a substantial increase in system complexity with little gain[4]. The system developed here is based primarily on the measurement of shaft speeds and temperature, with further capabilities if pressures and fuel flow are available.

(*d*) *Low Cost*—Bearing in mind that performance monitoring is only one aspect of an EHM system, and not necessarily the most important one, it is clearly important to provide a low-cost system. The use of a programmable calculator in conjunction with the existing instrumentation provides a low-cost system with negligible risk and a good potential for successful operation in the field.

(*e*) *Increased Operator Participation*—It is frequently claimed that manual data gathering is unreliable and subject to unacceptable errors. The authors' experience, however, has shown that, if the operator can become involved with the analysis of the data collected, there is a remarkable improvement in the quality of the data gathered; problems occur when operators merely collect large amounts of data that are passed on down the line and may never be heard of again, or not until a failure has occurred. The use of the programmable calulator greatly increases operator interest, and the rapid availability of performance data permits the operator to spot 'rogue' data immediately and repeat the necessary readings.

The system developed satisfies all the above requirements and should be readily acceptable to seagoing engineers. Informal demonstrations at sea have caused considerable interest and it is hoped that by the time the paper is presented some operational experience will have been achieved.

Gas Turbines to be Monitored

The majority of major warships of the R.N. and R.Nl.N. are powered by Rolls-Royce Tyne and Olympus engines using a COGOG arrangement, with the Tynes used for cruise and the Olympus for boost. Both engines use a twin-spool gas generator, with no variable geometry, and a free power turbine. In addition the cycle parameters for both engines are similar and the method of analysis developed is valid for either engine. The normal instrumentation is the same for both engines with the exception of temperature measurement on the earlier Tyne RMIA; power turbine inlet temperature (T_6) is measured on Olympus and Tyne RMIC, but on the RMIA LP turbine inlet temperature (T_5) is measured. In the COGOG arrangement the cruise engines run longer hours than the boost engines and for that reason more emphasis was placed on the Tyne, particularly with regard to examination of field data.

Choice of Programmable Calculator

A number of programmable calculators are quite suitable for the system proposed, including the Hewlett Packard HP 97 and HP 41C and the Texas Instruments TI 59. All provide an adequate memory and a printer for providing a hard copy of the data. The HP 97, however, is the only one which is built as an integrated unit combining the calculator and printer and this is particularly useful if the operator were to take readings at the local panel mounted on the module. A further advantage of the HP 97 for this application is that it can be operated on its own batteries independent of any external supplies, although only for short periods when using the printer. The TI 59 needs external power when using the printer and the HP 41C is arranged in a number of individual modules which have to be combined; neither of these features are desirable in this application. Previous experience with the HP 97 had shown it to be both rugged and reliable. The pace of development in the small calculator market is such that even better machines at a comparable price can be expected soon. It is the physical arrangement, packaging and power requirements that is likely to lead to the selection of a calculator, rather than its computing capacity.

General Approach

Before going into the details of the development of the EHM system to meet the requirements mentioned earlier, it is necessary to indicate briefly the approach adopted in the course of development

(*a*) The correction of data to standard day conditions.

(*b*) The adjustment of data to a reference condition.

(*c*) The comparison of data with baselines.

(*d*) Trend production and trend assessment.

Establishment of Baselines

One of the requirements of the EHM system described in this article is that the system must be capable of dealing with all engines of the same type. It is therefore undesirable to use individual baselines for each engine, as is sometimes proposed for computer based systems. The following points also illustrate that this approach is quite unworkable on board naval vessels.

(*a*) Readings have to be taken at a number of power settings to establish the baselines for the new engine. These readings have to be taken accurately from a stable engine, and special instruments may be required. This costs time and has to be fitted into the ship's programme.

(*b*) Computer facilities are needed to obtain the coefficients of the polynomials describing the baselines.

(*c*) There will always be a possibility of using the wrong baselines.

The requirement for general applicability of the system can only be met if one general set of baselines describing the parameters for each type of engine are used. This means that for one class of ships using two types of engine only two EHM programs recorded on magnetic cards are required. This will simplify paperwork considerably and will minimize the chance of mixing up programs.

In order to derive the set of general baselines from one type of engine, it was necessary to get an idea of the scatter likely to occur in practice. Actual engine data had therefore to be used. Data was collected from a variety of sources including ships of the Royal Navy and the Royal Netherlands Navy, the Naval Marine Wing of the National Gas Turbine Establishment (NGTE), R.N.A.Y. Fleetlands, and Rolls-Royce Ltd.

Data was thus representative of both that obtained under normal operating conditions at sea and the more rigorously obtained data measured on a test bed. The data from R.N.A.Y. Fleetlands provided the opportunity to check performance variation between engines returned from service and overhauled engines. Examination of pass-off test data from a considerable number of engines showed that the scatter of each parameter was not very large. This is illustrated in FIG. 1 where a typical mass plot of HP spool speed (N_H) versus LP spool speed (N_L) for the Tyne RMIC is shown. The line shown on this plot is the baseline fitted to these pass-off readings. In practice, the percentage deviation from the baseline for any parameter of a new engine will not be very large. In view of this and in view of the trend plots developed using the EHM system, it is important to recognize that it is not necessary to begin a trend plot with zero deviation from the baseline for each parameter; it is the percentage deviation change with time which is important. The percentage deviation of each parameter after installation of the new engine on board will represent the relative basis of the trend plot.

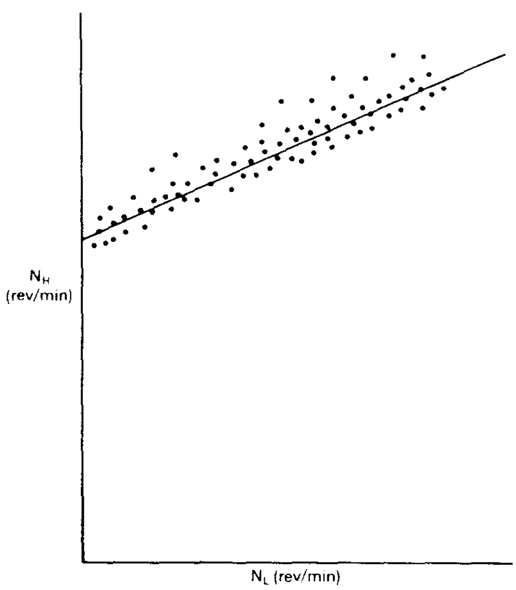

FIG. 1

Trend plot development

In order to compare data on an equal basis readings always have to be corrected to standard day conditions. Then a trend plot can be developed from comparing the corrected readings with baselines for each parameter. FIG. 2 shows a baseline for any selected parameter. The baseline describes the variation of the parameter with the independent variable N_L. Either N_L or N_H could have been used, but N_L is selected as the independent variable because it can be measured on board easily and accurately and varies over a wider range then N_H. The corrected value of the parameter for a given N_L is plotted at point A in FIG. 2. The system described in this paper will only use data taken within a moderate to high-power range (75 – 100 per cent.) because deterioration shows better at high than at low power. Within this power range a parameter can be assumed to vary approximately parallel to the baseline as shown in FIG. 2 by the dashed line through point A. In view of trend assessment where small change data expressed in percentage change are used, it is necessary to plot percentage deviation rather than absolute deviation from the baseline in the trend plot. It is therefore necessary to calculate the percentage deviation from the baseline at one reference speed, point B in FIG. 2, in order to get a comparison on an equal basis. Absolute deviation from the baseline will only be used to develop a trend plot of turbine temperature. It is important to monitor the magnitude of any rise in turbine temperature since running an engine at an excessive temperature will decrease life dramatically.

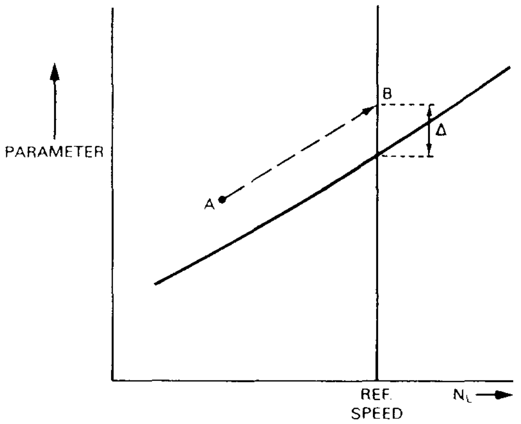

FIG. 2

The operator requires a continuous assessment of the engine to pick up a defect as soon as it occurs. Readings should therefore be taken and plotted frequently. FIG. 3 shows a typical trend plot where percentage deviation from the baseline of a parameter is plotted versus engine hours run. The point where gradual deterioration starts is also indicated on this figure.

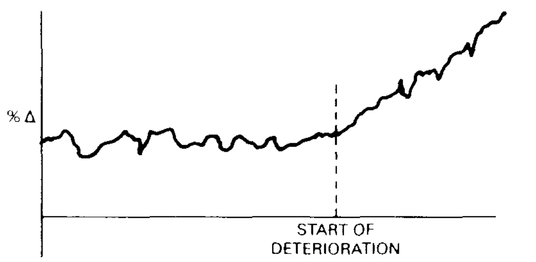

FIG. 3

Trend Assessment

The main problem of a performance monitoring system producing trend plot is the assessment of any observed changes of trends, either sudden or gradual. An operator is primarily interested in identifying a single defect as soon as it occurs. It is therefore extremely important to establish what the effect of any single defect will be on the thermodynamic parameters being monitored. This requires the establishment of small change data. The small change data were obtained from a mathematical model of a twin-spool engine derived from matching calculations. The effect of one single defect in the engine on all thermodynamic engine parameters was calculated. The percentage change of these parameters relative to the parameter values of a model engine was calculated and listed in small change tables. FIG. 4 shows an

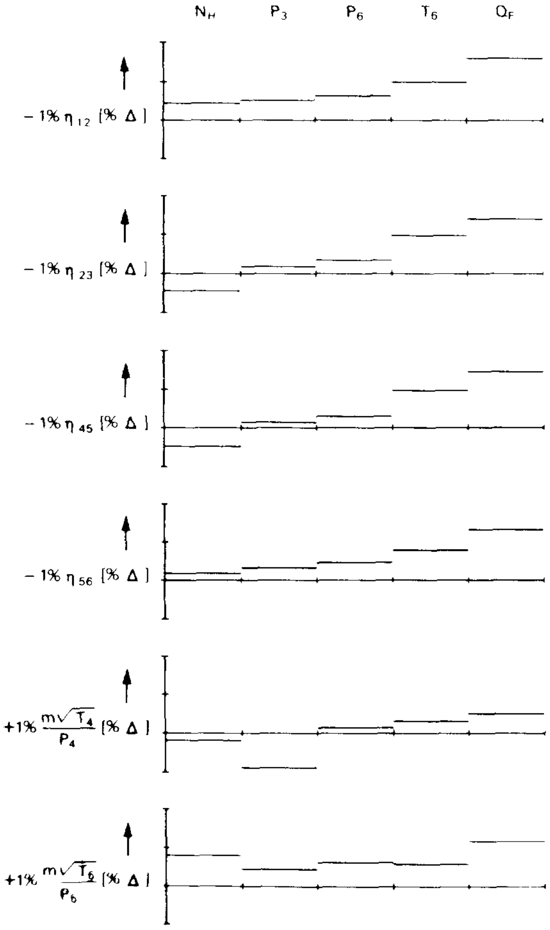

FIG. 4

example of such a table for a twin spool engine where the effects on parameters of several single defects are indicated. The effects of small changes (single defects) are very much the same for twin-spool engines which have similar cycle conditions, maximum temperatures and mechanical arrangements. It was also interesting to observe that there was a linear relationship between small changes in the range of one to five per cent.

The extent to which small change data can be applied for trend assessment is dependent on the thermodynamic parameters continuously monitored on board using the existing instrumentation. FIG. 5 was derived from the small change data and shows that a rising trend of N_H for a given N_L relates to LP spool deterioration and that a dropping trend of N_H for a given N_L relates to HP spool deterioration. This important observation which helps to differentiate between LP and HP spool deterioration will be called 'First Order Assessment'. Differentiating between compressor and turbine deterioration, referred to as 'Second Order Assessment', will have to be done using additional parameters. For the Royal Navy's present level of instrumentation this means only turbine temperature can be used for this purpose. This parameter offers the possibility of differentiating between compressor and turbine deterioration for the LP spool only. When more parameters are measured differentiation between compressor and turbine deterioration seems to be possible for the HP spool as well.

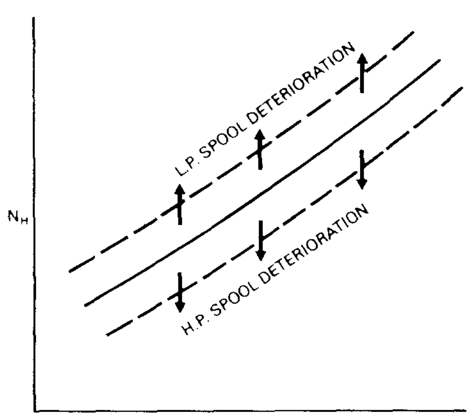

FIG. 5

The trend assessment method gives the operator an indication of the location of a defect, but does not indicate the degree of deterioration. A step change of several percentages, however, will certainly warn the operator that something serious has happened.

The MEO is being offered help in diagnosing why an engine is in trouble but he himself has to make the decision whether to keep going or not. In order to assist the MEO in making this decision, the system offers the possibility to estimate the operational effect of engine deterioration by relating rise of turbine temperature to loss of power as will be demonstrated later. The ability to detect to a particular level is useful but not necessary; naval propulsion engines are subject to repair by replacement of the gas generator, and are not designed to be split into individual modules. The method developed, however, is equally applicable to future modular engines which may be installed in remote locations where a module change would be advantageous compared with gas generator removal, and the ability to diagnose a faulty module is valuable.

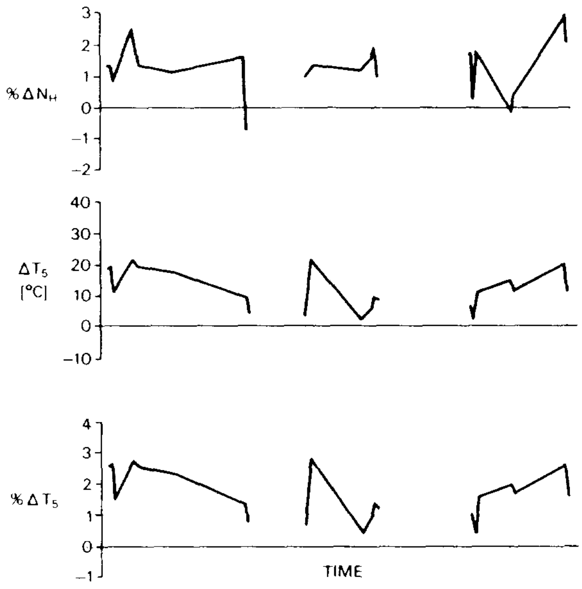

FIG. 6

Application at Sea

Data will be recorded manually by watchkeepers using the existing instrumentation; hence rotor speeds N_L and N_H and turbine temperature will be used. The data have to be recorded from a stable engine. It is therefore required that the throttle setting remains unchanged for five minutes before and during data recording and that data should be recorded as expeditiously as possible. The data must be selected as follows:

(*a*) Take all sets of readings recorded by watchkeepers over a period of 24 actual engine running hours.

(*b*) Select a set of readings meeting all the requirements of data recording and preferably taken immediately after a compressor washing. Also bear in mind that a set of readings with a high N_L is preferred.

(*c*) The selected set of readings has to be processed using the appropriate program for the programmable calculator.

(*d*) The percentage deviation of N_H and turbine temperature and the absolute deviation of turbine temperature have to be plotted versus actual engine hours run to form the trend plots.

FIG. 6 shows the trend plots of a Tyne RMIA from a R.N. ship developed using the method described above. The data were recorded manually from the existing instrumentation over a period of five months. The engine had been in service for approximately 1800 hours when this data were first taken so no basic trend of the new engine was available. The scatter is what can be expected of manual data gathering and there is no visible deterioriation. Application on board of the EHM system, however, will most likely reduce the scatter.

It is interesting to demonstrate what can be done when more parameters are monitored continuously. This can be illustrated by analyzing data obtained from the National Gas Turbine Establishment (NGTE) on a development engine. This engine was put on a standard marine endurance trial, which meant heavy salt ingestion throughout the trial and extended operation at high-power settings. The trial was primarily meant to assess the durability of some new HP turbine blade coatings. Compressor washing was carried out every 24 running hours. The readings used for this analysis were taken immediately after every compressor washing. Early in the trial, following a fuel pump failure and a series of hot starts, a change in engine performance was observed and analysis by Rolls-Royce indicated a probable increase of LP

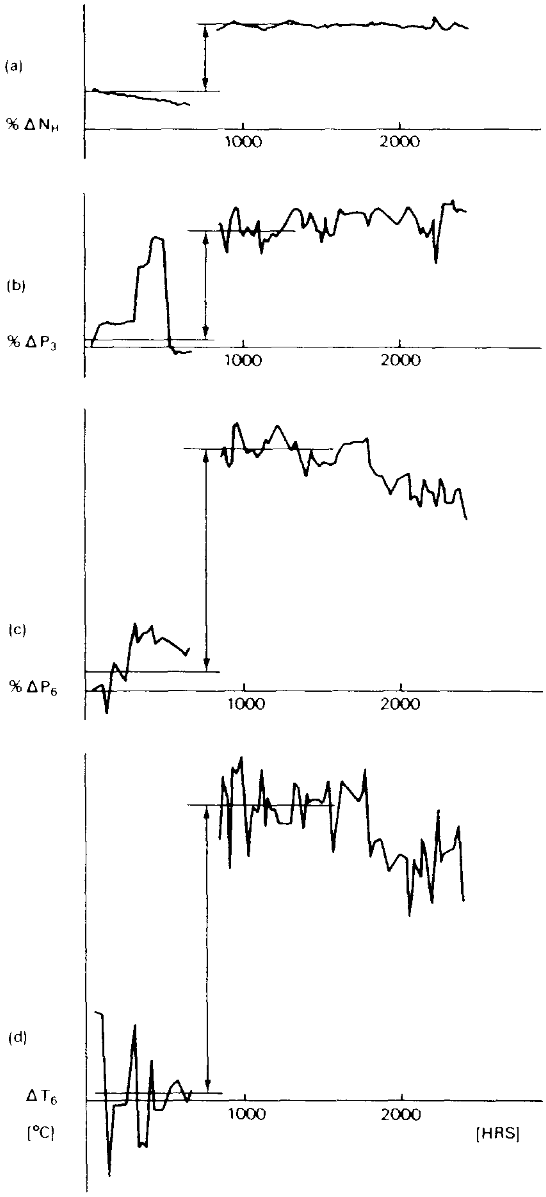

FIG. 7

turbine nozzle area. Trend plots of N_H, HP compressor exit pressure (P_3), power turbine entry pressure (P_6), and T_6 were obtained using the EHM program and are shown in FIG. 7. The basic trends of the new engine are indicated on the trend plots and the step change of trend after the fuel pump failure is clearly visible. The basic trends of the engine are for most parameters non zero partly due to the normal scatter one can expect using general baselines and partly due to calibration difficulties at the beginning of the trial.

First Order Assessment of the step change of trend indicates LP spool deterioration due to the rise of N_H. Differentiating between compressor and turbine deterioration for the LP spool, Second Order Assessment, was also possible. FIG. 8 assists in Second Order Assessment and shows the three triangles each built from the percentage change of P_3, P_6, and T_6 for a 1 per cent. change of N_H for a single defect. These percentage changes were obtained from small change data. The single defects are LP compressor efficiency drop, and LP turbine nozzle area increase. When the trend changes of P_3, P_6 and T_6 for a 1 per cent. change of N_H, obtained from the trend plots, are plotted on an overlay of FIG. 8, it is clear that the triangle representing these trend changes matches best with the triangle representing LP turbine efficiency drop. Although analysis by Rolls- Royce after the fuel pump failure indicated LP turbine nozzle area increase, which was later confirmed by the strip report, it is clear that the distorted flow through the nozzles will cause the LP turbine efficiency to drop. One could conclude therefore that this system would have correctly diagnosed the LP turbine as the defective component.

FIG. 7d shows the step change of T_6 after the fuel pump failure. This step change can be used in FIG. 9 to estimate the power loss that the engine suffered. Point A on FIG. 9 is obtained from plotting the step change of T_6 from the baseline at the reference speed (N_L REF). The line through A parallel to the baseline represents the variation of T_6 with N_L after the fuel pump failure. The maximum temperature (T_6 max) is reached for this condition at point B at a lower speed (N_LB) than the maximum speed (N_L max). This new maximum speed (N_LB) causes a loss of power indicated in FIG. 9b where power is plotted versus N_L. The power loss derived is a rough estimation but it gives the MEO at least an idea of the severity of the defect. One should bear in mind, however, that this method is rather conservative, because running at a lower speed at maximum temperature decreases stresses in the turbines.

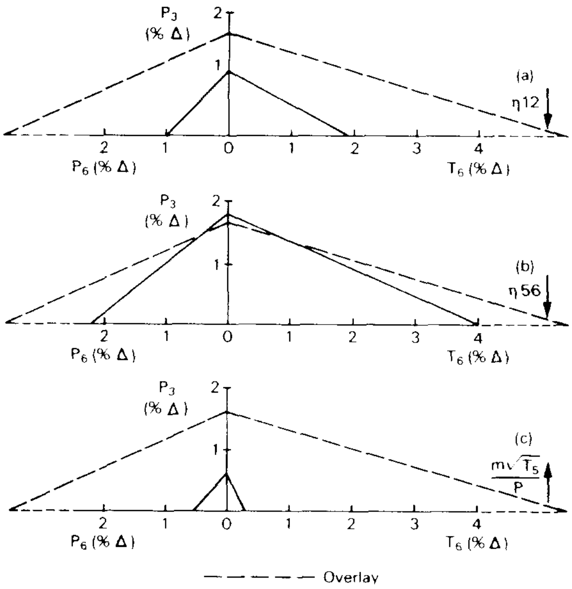

FIG. 8

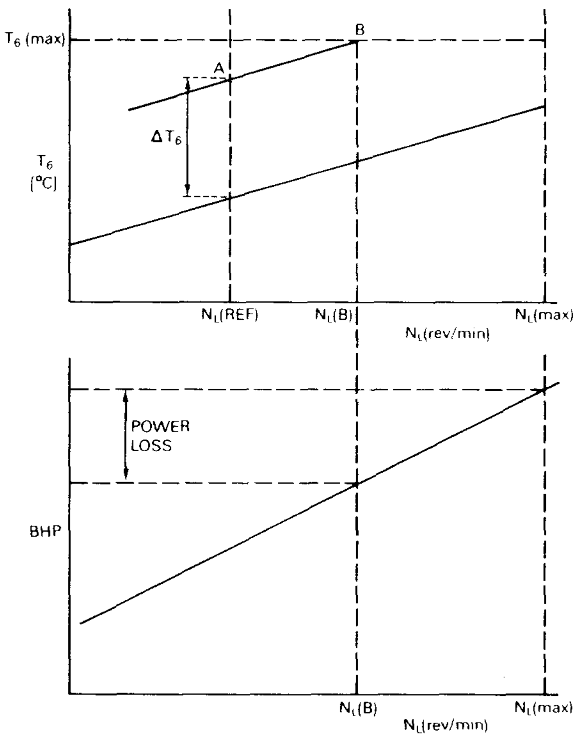

FIG. 9

Conclusions

A low cost onboard EHM system has been developed. The system uses existing instrumentation monitoring engine parameters continuously. This means that only N_L, N_H and T_6 are used. The programmable calculator used for data processing proved to be an invaluable tool, giving the operator rapid feedback and minimizing work load. The trend plots developed using the system give the operator the required continuous assessment of engine performance. Engine deterioration, or the occurrence of a defect, result in gradual or sudden trend changes that should be noticed by the operator. The operational effect of engine deterioration or a defect can be determined since the operator can relate rise of turbine temperature to loss of power. Trend assessment also offers the operator the ability to differentiate between HP and LP spool deterioration from a simple observation of speeds. With pressures P_3 and P_6 and turbine temperature (T_6) monitored, differentiation to the component level for the whole engine is possible.

Acknowledgements

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The views expressed in the paper are those of the authors and are not necessarily those of the Ministry of Defence.

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Comment by D.G. Ships

The approach to performance monitoring developed in this article is of great interest to D.G. Ships and it is hoped to establish the viability of the method at sea in ship trials in the near future. If these are successful, consideration will be given to the introduction of the method into all Tyne and Olympus ships, together with an extension to include P_3 and probably P_6 monitoring as well.