MARINE GAS TURBINE CONDITION MONITORING BY GAS PATH ELECTROSTATIC DETECTION TECHNIQUES

BY

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ABSTRACT

This article outlines the theory that certain gas turbine failures are preceded by a change in electrostatic activity in the exhaust gases. During trials at the Admiralty Test House, the Ingested Debris Monitoring System and the Engine Distress Monitoring System demonstrated that electrostatic monitoring at engine inlet and exhaust can identify the ingestion of debris, consequential engine damage and the onset of unexpected distresses caused by blade rubs or combustor degradation. The principle shows potential to provide early warning of certain types of engine damage at sea. Development work to provide a rugged condition monitoring system continues.

Introduction

Background

Research and investigation into the use of electrostatic techniques to monitor the condition of a jet engine or gas turbine gas path commenced in America in the early 1970s. This work, reported by Couch[1], demonstrated the potential of the technique but appeared to cease in 1979.

Stewart Hughes Limited (SHL) saw the potential of the technique but recognized the need for a basic understanding of the fundamental principles. An initial feasibility study and consequent research programmes were undertaken, funded and sponsored by the Propulsion Department of the Royal

Aerospace Establishment, Pyestock (RAE(P)). Details of the research programme and subsequent development programmes were given by Fisher[2].

Recent development programmes funded by MOD (PE) will lead to flight trials of the technique on Tornado and other fixed and rotary wing aircraft. Two systems are being developed; the Engine Distress Monitoring System (EDMS) for monitoring debris in the gas path, and the Ingested Debris Monitoring System (IDMS) for monitoring debris ingested into the engine intake. These systems sense the disturbances in the electrostatic field of the exhaust and inlet gas paths as debris particles pass through. The signals so produced are conditioned and processed for online or later analysis.

The potential benefits of these systems to marine installations were recognized, in 1983, by the Admiralty Test House (ATH) at RAE(P), now part of the Propulsion Department. SHL were subsequently contracted by MOD(Navy) to conduct a series of trials on Rolls-Royce engines both at Ansty and Pyestock. A general schematic of the two systems for installation on a marine engine is shown in Fig. 1.

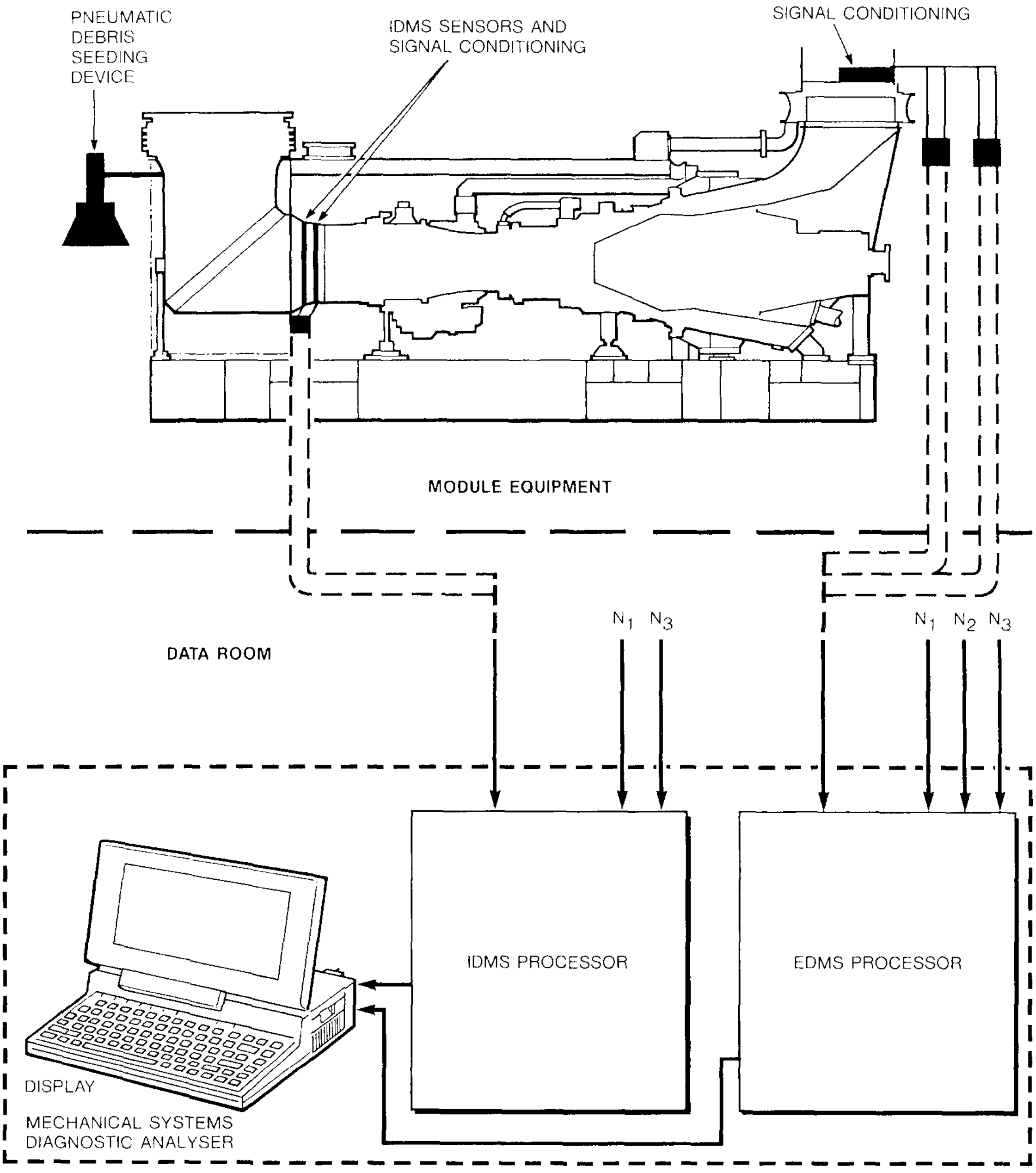

FIG. 1—OVERALL SCHEMATIC OF INGESTED DEBRIS MONITORING SYSTEM (IDMS) AND ENGINE DISTRESS MONITORING SYSTEM (EDMS), APPLIED TO A SPEY SM1A

Admiralty Test House Trials

Initial trials of EDMS were conducted at the ATH in 1987 on a Marine Spey SM1A gas turbine change unit (GTCU). A fuller evaluation of both EDMS and IDMS was gained during a subsequent 2000 hours endurance trial between June 1988 and August 1989.

To investigate the electrostatic signature of a variety of different debris particles and establish the full capability of IDMS to distinguish between debris sample types, a programme of seeding trials was proposed and funded by RAE. It was considered highly likely that engine damage would result from these trials, which would produce useful data for further validation of the EDMS. These trials were completed in December 1989.

This paper reports on the progress in the development of the IDMS and EDMS, presents the results of the seeding trials, and discusses the recommendations for further utilizing this most promising condition monitoring technique.

Principles of Operation

The principle of the gas path monitoring technique is to monitor the electrostatic charge carried by particles present in the engine gas stream. This is achieved by monitoring the electrostatic charge induced on suitable sensors mounted in the gas path.

Engine Distress Monitoring System

The exhaust gas has a normal level of electrostatic charge which gives the background signal. Metal strip sensors, electrically isolated from the wall structure, are situated around the uptake immediately downstream of the exhaust volute. The signal produced from these will change when increased amounts of charged debris are present in the gas. This may be due to various reasons:

(*a*) Fault-produced debris in the gas path, such as from blade rubs, fretting, combustor burns, etc.

(*b*) High levels of carbon being formed in the combustion chambers and being shed.

(*c*) Wear of abradable seals/coatings.

The EDMS signal is analysed in both the time and frequency domains. In the time domain two parameters are identified:

(*a*) The Activity Level parameter gives an indication of very small particles in the exhaust gas. They are usually smoke and small carbon particles. The Activity Level is also affected by small particles of metallic debris.

(*b*) The Event Rate parameter gives an indication of larger particles in the exhaust gas at any time. It is sensitive to large pieces of carbon, probably produced by carbon build up and shedding, and to the larger pieces of metallic debris typically produced by faults.

The signal is also analysed to establish whether any debris production is periodic and related to the shaft speed, giving an indication of blade or case rubs if they occur.

A baseline for each of these parameters is established when the engine is in a known healthy condition. Baseline levels increase as a function of the engine power level which may be monitored from low pressure spool speed or torque.

Ingested Debris Monitoring System

In the marine application, the filter on the intake means that in normal circumstances no debris should pass into the intake; however the intake is a large convoluted structure and foreign object ingestion and subsequent damage has been known to occur. A pair of screened metal tape sensors are stuck to the outside of the fibreglass intake flare, immediately upstream of the compressor inlet. Electrostatic signals from these are conditioned and processed for analytical techniques similar to those of the EDMS to be used to give indication of:

(*a*) Dust/salt etc. due to filter breach or faults using the Activity Level parameter.

(*b*) Larger particles or foreign objects from the Event Rate parameter.

The Trials

The equipment installation was similar to that shown in FIG. 1, with the exception that the data was either tape-recorded or logged and analysed on the SHL Mechnical Systems Diagnostic Analyser as the processors are still being developed and tested at SHL.

Data was recorded at a number of intervals during the 2000 hours, with continuous monitoring for the final 100 hours. The trial was undertaken in two 1000 hour stages with a full engine strip inspection between stages.

Engine Distress Monitoring System

The feasibility of using EDMS to monitor the exhaust gas path of marine gas turbines had been previously demonstrated on Tyne engines at Rolls-Royce, Ansty, and on board HMS *Newcastle.*

The aim of the EDMS trial at RAE(P) was to evaluate the ability of the equipment to monitor the material condition of the gas turbine throughout the 2000 hours of the trial. This was to be achieved by the following objectives:

(*a*) Establishment of a large data base to represent the performance patterns of the equipment during an extensive period of engine life, in the expectation that the signal trends would reflect any deterioration in the engine.

(*b*) Assess the capability of the sensor units to withstand the hostile environment of the exhaust, to which end regular inspections were conducted.

(*c*) Design and evaluation of a system check device for use on both EDMS and IDMS.

Ingested Debris Monitoring System

The principles of IDMS had already been demonstrated on aircraft engines. The marine environment differs significantly from the runway conditions suffered by aircraft. The inlet air is filtered to remove all but a tiny proportion of the marine aerosol and particulate debris. However, the inlet ducting is of much greater proportion and convolution than the aero equivalent. There is therefore a risk that particles entrapped during manufacture or cleaning could be liberated during subsequent engine running. In addition, it has been known for the structure itself to generate particulate matter during the normal course of operation in the marine environment. These sources of foreign object damage (FOD) have led to a number of early engine rejections in the RN shipbuilding programme.

The aim of this IDMS trial, therefore, was to establish the feasibility of electrostatic debris detection in the marine environment.

Debris Seeding Trials

The trials described so far aimed to demonstrate the techniques of electrostatic detection within the gas path of a healthy engine and gain suitable background running information for the test engine.

A series of debris seeding trials was then undertaken, where examples of typical downtake debris and powdered engine component materials were injected into an engine running at near full load conditions. It was convenient that a spare GTCU, capable of running but beyond normal operational levels of hot end damage, was available for trials purposes.

The objectives of this work were:

(*a*) To establish signal characteristics of the IDMS and EDMS produced when a variety of foreign objects and typical engine distress samples are seeded into the engine.

(*b*) To explore the discrimination capabilities of the IDMS to distinguish between potentially damaging and non-damaging debris.

(*c*) To explore the detection capability of the EDMS for typical materials used in the construction of the gas turbine, should consequential damage occur from the debris ingestion.

(*d*) To explore the possibility of discriminating between damaging and non-damaging ingested materials using IDMS and EDMS.

(*e*) To establish possible warning and alarm indicators for the IDMS and EDMS signals.

Having established the engine's IDMS and EDMS footprints before the ingestion commenced, the engine was run at 75% power and specified quantities of each material injected, using LP air, into the engine downtake. The materials selected for ingestion tests were:

- dust
- cellophane pieces
- Al fine and coarse powders
- Fe fine and coarse powders
- Ni fine and coarse powders
- Ti fine and coarse powders
- nickel X40 coarse powder
- Inconel 601 fine powders
- Sherritt Gordon ceramic
- Metco 301C ceramic
- match
- cigarette end
- card strip
- silicate sand
- mineral fibre
- one grain of bead blast
- two grains of bead blast
- 0.5 cm^3 of bead blast grains

Analysis of Results

Engine Distress Monitoring System

The results and interpretation presented here are based on data from the second 1000 hours of the trial. Similar results were obtained from data from the first 1000 hours.

The Activity Level and Event Rate baselines were established over several hours running at the start of the 1000 hours when the engine was in a known healthy condition. FIG. 2 shows data obtained during a baseline performance map. The variation in the two parameters with engine operating condition is evident. Frequency domain analysis showed no evidence of shaft order related effects.

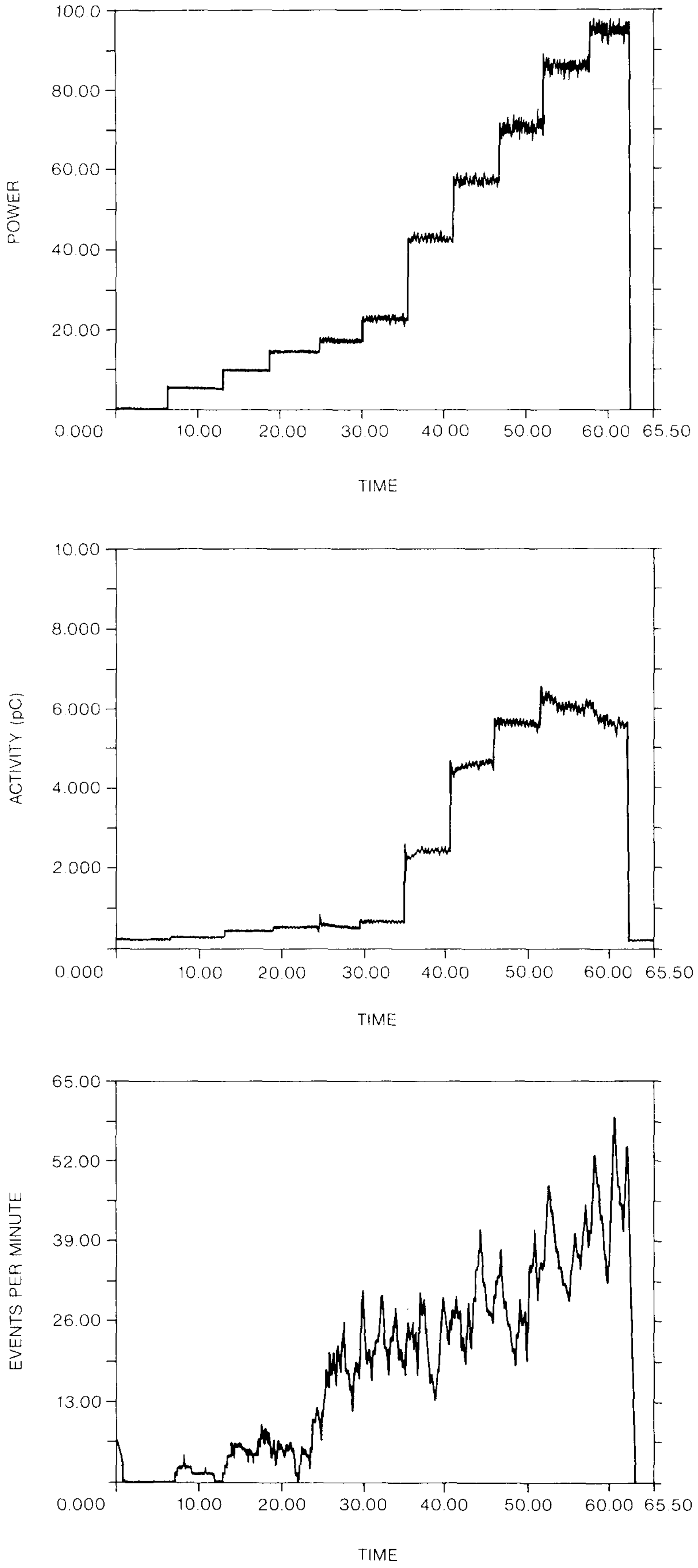

FIG. 2—EDMS BASELINE PERFORMANCE MAP DATA

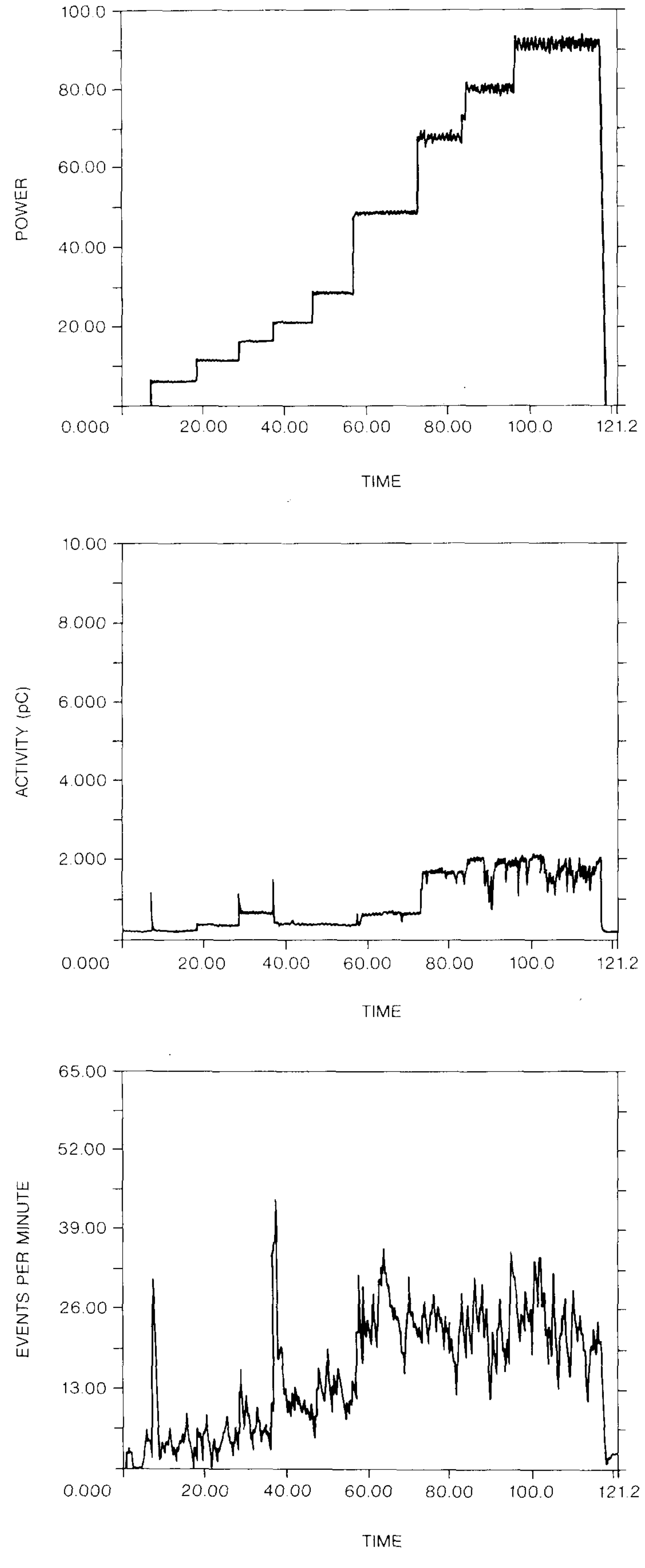

FIG. 3—EDMS PERFORMANCE MAP DATA AFTER 400 HOURS OF NORMAL RUNNING

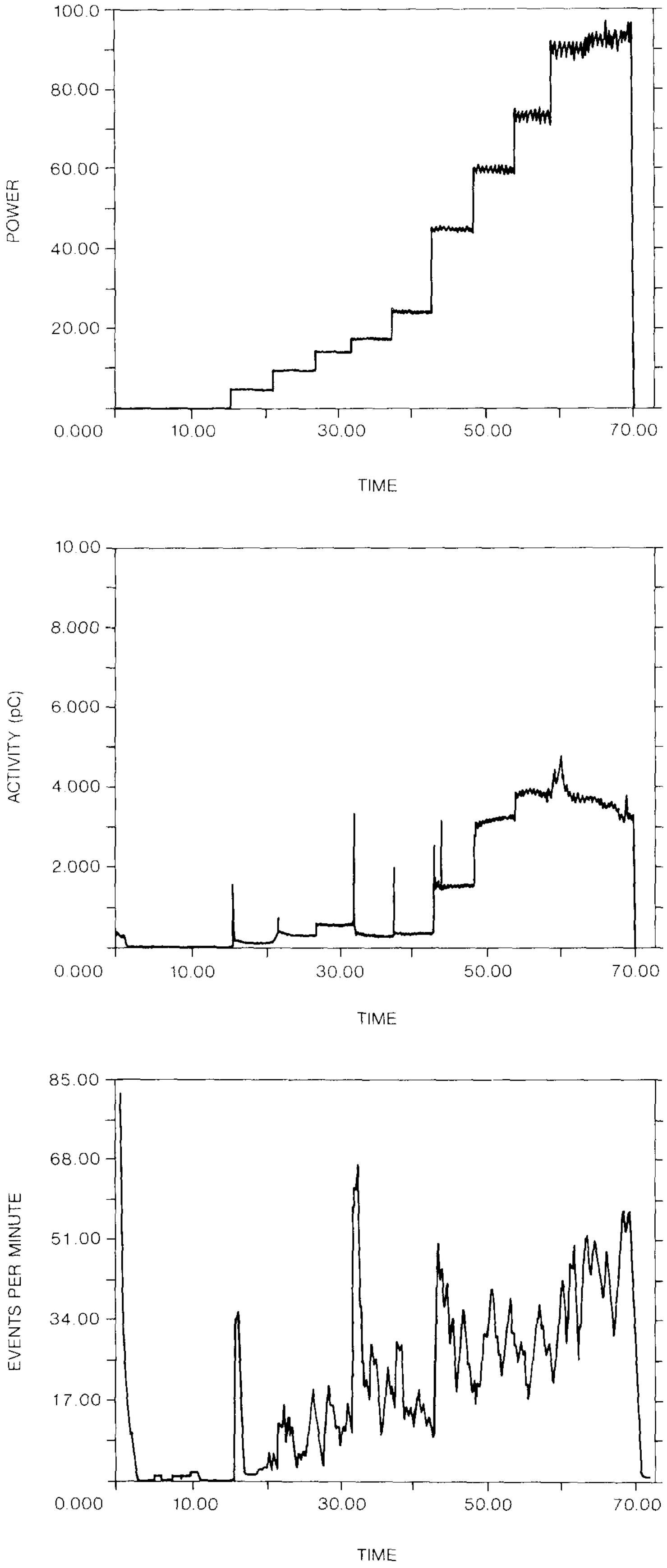

FIG. 4—EDMS PERFORMANCE MAP DATA AFTER 900 HOURS OF NORMAL RUNNING

FIGS. 3 and 4 show data from performance maps approximately 400 and 900 hours into the trial, which are typical of results obtained as the trial progressed. Marked changes in both parameters can be seen compared to the baseline.

(*a*) At 400 hours (FIG. 3) the Activity Level has increased at the 15% power condition, but from 45% power upwards the levels have significantly decreased, with no demarkation between the changing power levels.

(*b*) The overall Event Rate has increased at the lower powers, particularly around 5%, 15% and 45% but has reduced at the higher powers.

(*c*) At 900 hours (FIG. 4) the Activity Level shows large peaks on accelerations, an increased level at 15% power and reduced levels at the higher powers.

(*d*) The overall Event Rate shows significant increases at the lower powers and particularly at 45% power.

There was no evidence of shaft order related effects.

The negative to positive event count ratio was also analysed. This showed that during periods when the Activity level was low, the ratio was high, i.e. a larger number of negative events. Increases of Activity Level at the lower powers (15% and 18%) correspond to a decrease in the ratio, i.e. a larger number of positive counts.

The EDMS results show that significant changes occurred in the condition of the gas path of the engine during the trials, indicated by the changes in the signals outlined above. Monitoring for any of the variations would indicate that the engine was suffering deterioration or that the combustor performance had changed. Due to the nature of this trial, with regular engine inspections and with knowledge built up during the first 1000 hours of the trial, it was possible to build a picture of the nature and progression of the minor combustor degradation that occurred.

Initially the degradation caused a minor change in the combustor performance, shown by the increase in Activity level at 15% power indicating that more smoke and carbon were being produced at this power. This was confirmed by correlating the EDMS data with monitored smoke data. As the degradation progressed, the change in combustor performance at the 15–18% powers continued but material was lost from the combustors at the mid power range, most notably 45% power. Again correlation with the smoke data showed baseline smoke production but a large reduction in Activity Level and an increase in negative event count. Confirmation that this was due to metallic debris was achieved later in the debris seeding trials also outlined in this paper.

The degradation appeared to progress, then stabilize and then progress again throughout the duration of the 1000 hours. Towards the end of the trial, EDMS showed evidence of degradation occurring between 30% and 60%, with a continuing effect on the combustor performance shown at 15–18% powers.

The value of the EDMS as an on-line monitoring technique was successfully demonstrated during this trial, providing an early warning of even minor combustor degradation.

Ingested Debris Monitoring System

The main objective of this work was to demonstrate the feasibility of applying the IDMS technology to the marine environment. One of the main areas of work was to optimize the sensor installation in this environment, which is very different to that found on aircraft. An advantage of this application is that the intake duct is made of glass reinforced plastic and is therefore an insulator. Two IDMS sensors were installed on the GRP engine intake. The sensors are of a composite tape construction and adhere to the external surface of the intake flare, thus having no effect on the air flow or safe operation of the engine.

The test results showed that the normal background signals were of low amplitude and repeatable. Data analysis was carried out using the same techniques as for the EDMS and the results proved this to be a feasible option. This will make integration of IDMS and EDMS technology in the marine environment simpler.

From time to time small foreign objects were detected being ingested, on the Event Rate parameter which was normally zero. During inspection of the sensors, small quantities of foreign matter (rust particles from the downtake structure) were found in the intake region, which would account for these IDMS indications.

The tests were successful in demonstrating the feasibility of the IDMS in the simulated marine environment and much progress was made in improving the sensor systems.

Debris Seeding Trials

Further engine trials were carried out which involved seeding debris into a SM1A engine to explore the detection capabilities of IDMS and EDMS.

The trials were very successful and the overall objectives of the work were achieved. IDMS was seen to have an apparent 100% detection capability for all seeded debris that entered the engine. Evidence from post seeding inspections, which were conducted at the end of each seeding serial, indicated that those items that were not detected on IDMS probably did not enter the engine.

Discrimination between powders and single objects is possible with the two-sensor IDMS configuration. FIGS. 5(a) and 5(b) show typical IDMS signals for two grains of bead blast material and a fine powder respectively.

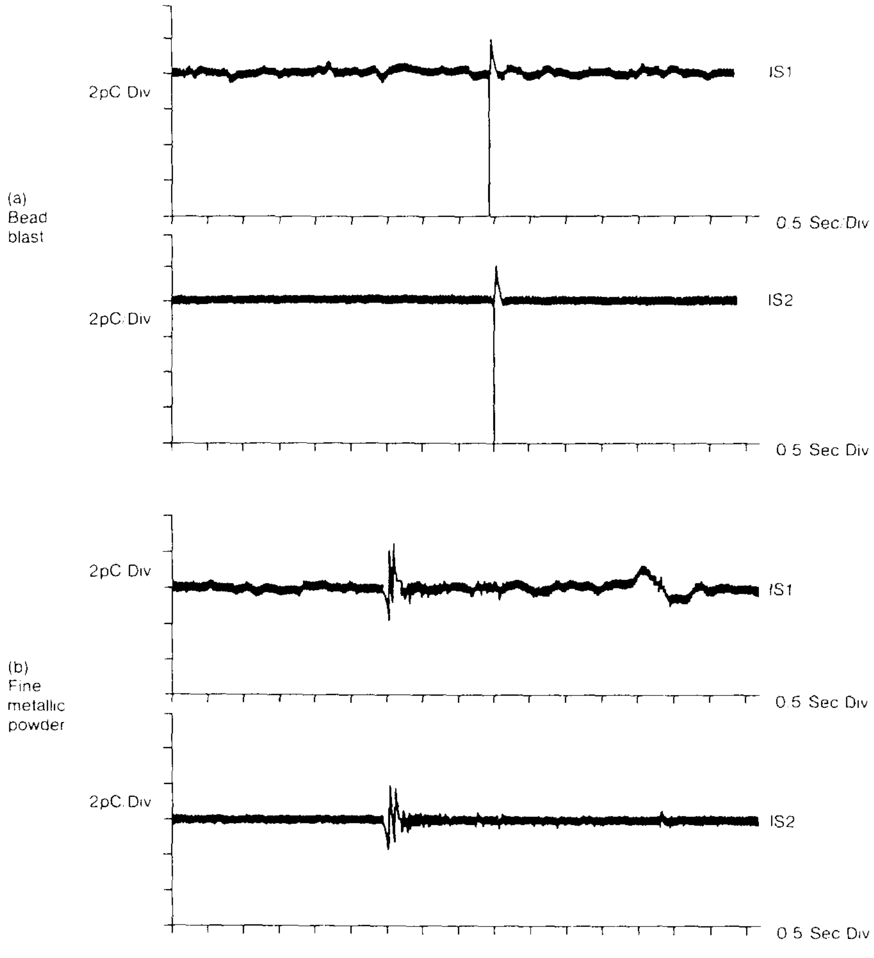

FIG. 5—IDMS SIGNALS FROM SEEDED DEBRIS

A greater degree of discrimination is possible using a three-sensor configuration and more complex processing techniques. This is the system used on aero-engines, where the engine is susceptible to ingestion of a wide variety of debris, much of which is non-damaging. However, in the marine environment, where extensive filtration systems are utilized, it is assumed that the ingestion of any debris is undesirable; hence the simpler IDMS configuration has an adequate capability.

The IDMS results proved to be repeatable and gave excellent correlation between signals from sensors IS1 and IS2.

Interference effects were seen simultaneously on IS1 and IS2 sensors at frequent intervals. These were thought to correspond to an engine control signal to the throttle stepper motor, as they corresponded to a consequential effect seen on the EDMS sensors some 20–40 mSec later.

Warning/Alarm indication for IDMS may be achieved by monitoring changes in Activity Level and Event Rate, which under normal operating conditions are constant, Event Rate being zero.

After the seeding of each sample, the consequent effect was clearly apparent on the EDMS footprint. The reduced Activity Levels, seen on EDMS following the ingestion of metallic debris, were consistent with the results of the 2000 hours trial when combustor degradation was seen to produce this effect at higher powers.

Warning/Alarm indications are also possible for EDMS. It has been confirmed by this trial that changes in Activity Level and/or Event Rate correspond to the presence of debris. In this trial, frequent correlation was seen between IDMS events following ingestions and changes in these parameters on EDMS.

Conclusions

The systems described in this paper have demonstrated their ability to give on-line detection of gas path events in a marine installation. The benefits of using these systems during the evaluation of the marine gas turbines are many but include the following major advantages:

(*a*) The use of IDMS confirms that the air consumed by the engine under test is free from ingested debris. Should any foreign object pass into the engine the event can be noted and considered during subsequent endoscope inspections.

(*b*) The IDMS traces may be used to either identify or exclude FOD from the list of contributory factors, should catastrophic failure of gas path components occur.

(*c*) Analysis of EDMS data gives warning of frequency-related defects within the engine, such as blade or seal rubs, that no other system can detect. This is particularly relevant in the evaluation of latest generation engines, where seal technology is continuing to develop.

(*d*) EDMS may be used to give indication of the power level at which combustor and other gas path degradation occurs. It is commonly assumed that such degradation occurs predominantly at maximum power. During the 2000 hours trial, the EDMS demonstrated that a significant part of the degradation occurred at 15% and 45% power levels.

In view of the experiences gained with these systems, the IDMS and EDMS should prove to be important tools in the evaluation of the 20 MW Rolls-Royce SM1C marine gas turbine during the forthcoming trials at the Admiralty Test House.

References

1. Couch, R. P.: Detecting abnormal turbine engine deterioration using electrostatic methods; *Proc. American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Conference, August 1978*, paper no. 78-1473.
2. Fisher, C.: Gas path condition monitoring using electrostatic techniques; *AGARD Conference Proceedings* No. 448, June 1988.