Engine Health Monitoring: Towards Total Prognostics

H.E.G. Powrie and C.E. Fisher
Stewart Hughes Limited
School Lane
Chandlers Ford
Hampshire, SO53 4YG
United Kingdom
+44 (0)1703 242000
hep@shl.co.uk and cef@shl.co.uk

Abstract—As advanced aircraft gas turbines are developed with increased performance and service life, emphasis is placed upon engine health monitoring (EHM) to reduce direct costs such as hardware, labour, fuel and logistics. The ultimate goal for EHM has been set by the Prognostics and Health Management (PHM) program for the Joint Strike Fighter (JSF) aircraft. The vision is a combined monitoring system that will enable the aircraft to report its own engine problems, thereby minimising operational and support costs. This is a highly advanced concept, which necessitates significant evolution from the current state of the art.

As the first step towards total engine prognostics, a suite of EHM systems has been identified for monitoring the different aspects of the engine's health. These include new and emerging technologies, which are essential if a full picture of the engine's condition is to be determined. The suitability and maturity of the EHM systems are to be proved by means of two seeded fault engine tests (SFET), funded by the JSF development program.

This paper details three emerging technologies selected for the JSF SFET program. The EHM systems described offer potential monitoring capabilities that are not easily achievable with existing technology. The key functionality of each system is described together with a review of its performance during the first SFET—

TABLE OF CONTENTS

1. INTRODUCTION

Total prognostic health management (PHM) offers aircraft operational cost and safety benefits above and beyond any strategy currently used. The PHM initiative covers a number of aircraft systems of which the engine is one such system. The required input for aircraft PHM is an assessment of the engine's health. This is not just the current health status of the engine but includes future maintenance requirements, as these tasks have to be planned in with the intended aircraft usage. The way to achieve this information is via engine health monitoring. For this reason EHM technology forms a cornerstone of total PHM.

In the first stage, the engine sub-systems which require monitoring must be determined. The decision may be influenced by probable engine faults or faults with potentially serious consequences. These could, in turn, depend on factors such as mission profile, aircraft operational environment and so on. Once the monitoring requirement is defined, suitable technologies must be chosen. This is a difficult task as health monitoring exists for the many engine sub-systems, incorporating varying complexity and functionality. In addition there are developing technologies which will improve or even replace existing technology. While the combination of EHM systems must be capable of supplying full engine information, it is important that the search for the best solution addresses integration of multi-sensor data in order to minimise equipment fit and maximise status information.

The three EHM systems described in this paper provide engine condition data which are not readily available from other technologies. The Engine Distress Monitoring System (EDMS) detects the electrostatic charge associated with debris present in the exhaust gas of a jet engine. The EDMS monitors gas path component deterioration in real time and provides early warning of incipient fault conditions. The severity of the fault may be tracked, thereby allowing greater freedom in maintenance planning. Fault discrimination to engine module level is possible and so EDMS may be used to promote timely application of fault specific diagnostics. EDMS also monitors faults, for example combustor degradation, which are not readily detected by other techniques.

The Ingested Debris Monitoring System (IDMS) has been developed to detect and discriminate foreign object (FO) ingestion. There is no fully proven on aircraft method for detection of FO and consequential damage, however IDMS is a potential technology. Similar to EDMS, IDMS detects the electrostatic charge carried by debris ingested into the engine. When a piece of debris is detected, certain characteristics are combined to produce an assessment of its damage potential (i.e. non-damaging or damaging). The data is correlated with EDMS results to determine the resultant effect of the ingested object on the engine.

Electrostatic detection technology is currently being developed to monitor oil-borne debris. The oil-line sensor (OLS) addresses shortcomings in existing systems such as detection of 'fines' and non-metallic particulate, which includes ceramic bearing coating material. A wear-site sensor (WSS) has also evolved: This is mounted close to contacting surfaces for early detection of oil system component deterioration. The WSS is particularly relevant for monitoring flight critical components prone to rapid deterioration and / or hazardous failure.

Whichever EHM technology is required, the prognostic and diagnostic capabilities of each monitoring system must be understood. Systems sensitive to the early stages and progression of a fault may not be able to discriminate to the level of detail desired. For example, if the system detects the physical effects associated with the early stages of a fault and not the grosser characteristics which occur once the fault is fully developed. Conversely, detailed diagnostic systems may lack early detection capability. However, both early detection and accurate discrimination are important if a useful picture of the engine's health is to be determined. As a minimum this picture includes the present and near term future. For this reason data integration will play an significant role: Just as engine sub-systems are combined to provide a fully functional engine, then so must health monitoring techniques be integrated to produce the complete engine health status. Although the main issues relating to technology integration and data fusion are beyond the scope of this paper, the benefits of data integration are highlighted. Integration of EDMS, IDMS and engine operational data, to provide a more robust prognostic result, is discussed.

New technologies require time to become proven and programs such as the JSF SFET will help assess system maturity and reliability. Once a system has been developed to the point where its functionality can be defined, reliability and maturity issues can start to be addressed. Seeded fault tests are a means of rapidly accruing system performance data, such as false or missed alarm rates and probability of detection. These are important factors in the final selection process. The implications of system performance is demonstrated using the IDMS data.

2. EHM Technologies

EDMS

This section provides a brief overview of the EDMS technology, including implementation. Further information is presented in References [1] and [2].

Overview of Functionality—The basic principle of the Engine Distress Monitoring System (EDMS) is to monitor the electrostatic charge associated with debris present in the exhaust gas of a gas turbine or aero-engine. The exhaust gas of a healthy engine has a normal level of electrostatic charge which varies with the operating condition of the engine. The normal level is used to calculate a baseline reference or threshold from which deterioration in engine performance may be determined. The threshold calculation allows for a certain degree of deterioration due to normal engine usage.

When gas path component deterioration occurs the system detects significant changes in the overall electrostatic charge level due to the increase in debris present in the exhaust gas, produced by the fault.

When gas path component faults such as blade rubs, nozzle guide vane erosion and combustor burning occur additional debris is present in the exhaust gas. This change is detected by EDMS and fault specific signal characteristics can be used to identify the type of fault producing the debris.

These changes are distinct from normal engine deterioration. Other situations can also result in increased debris in the exhaust gas, such as ingested material or objects, new seals or rub strips rubbing in and some maintenance actions. In order for this technology to be effective it is important to be able to discriminate between these 'benign' situations and genuine faults. For example, the effects of maintenance actions are repeatable and diminish over a relatively short period of time and so the EDMS can be programmed to ignore these instances.

The PHM concept requires engine monitoring technologies that provide early warning of faults and the capability to monitor the development of faults so that timely action can be taken. EDMS has the capability to assist in meeting these goals – gas path faults such as the examples above typically produce debris from the earliest stage of the fault. EDMS can detect the debris as soon as it is produced and therefore provides an early warning of gas path component deterioration. Other monitoring techniques such as vibration and performance monitoring rely on monitoring a symptom of the primary fault. For example, in the case of a blade rub, vibration monitoring requires that adequate material is lost to result in an imbalance, performance monitoring requires that the resultant tip clearance is sufficient to affect the measured performance parameters. A combination of EDMS with these techniques ensures that an early warning and tracking of the progression of the fault are possible, with vibration and performance used to indicate the later stages of progression.

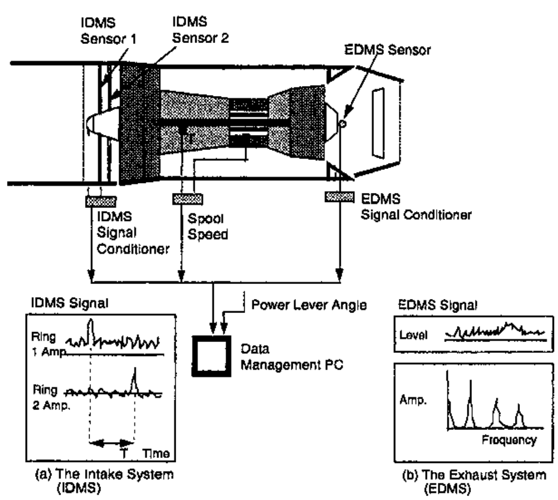

Figure 1 Schematic of IDMS & EDMS equipment

The capability for early detection also enables consequential damage to be minimised and timely maintenance carried out so that cost and time to repair are minimised. Continuous monitoring and correlation of the EDMS data with engine operating condition has also been shown to provide information that indicates if certain engine operating conditions are causing increased deterioration compared to other operating conditions. This information may be used to enable the engine operation to be altered, for example to allow a particular mission to be completed.

Implementation—EDMS comprises several system components as described below (see Figure 1). These have been developed and evolved with the objective of providing reliable, rugged and maintainable units.

EDMS Engine Mounted Equipment

The EDMS sensor is a passive device which is installed in the exhaust duct of the engine. The sensor concept has been developed over a number of years to minimise the size and weight of the sensor and to provide sensor designs that are relatively easy to install and maintain, whilst ensuring that the detection requirement is achieved. A typical sensor is shown in Figure 2.

In addition multi-function or integrated sensor concepts are being developed, with the objective of integrating the EDMS sensor function with other engine sensors to further reduce the cost and weight penalty associated with health monitoring.

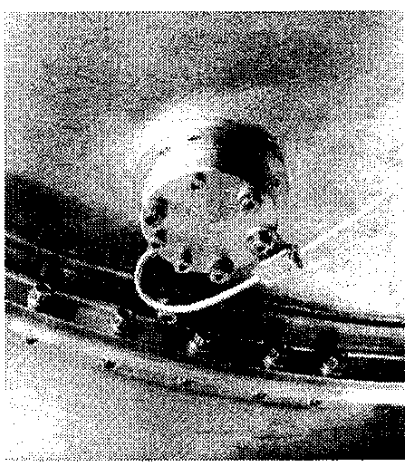

Figure 2 Typical EDMS Sensor Installation

One of the aims of PHM is affordability, this embraces the cost of the sensor itself, in terms of both initial cost and maintenance requirements, and the associated weight and installation modifications required for the sensor installation. By taking the multi-function sensor approach the impact can be minimised.

The sensor monitors electrostatic charge. The charge signal is then converted to a voltage signal using signal conditioning electronics. In previous engine tests this has been carried out using separate signal conditioning units, small off the shelf devices are currently under evaluation. In addition high temperature signal conditioning electronics, for integration on the sensor itself, is being considered. This has been designed to meet the environmental specification at the typical location of the EDMS sensor and will minimise the installation and maintenance requirements for EDMS.

EDMS Signal Processing and Signal Processor Equipment

The signal processing and analysis techniques have been developed from research and development activities as well as engine test data and inspection reports. The EDMS signal is correlated with engine parameters, such as spool speeds and engine power. The EDMS signal is processed to produce several signal components; namely activity level and event rates (both positive and negative) in the time domain and shaft order components in the frequency domain. These have been shown to relate to the production of debris from engine faults. Reference [1] describes the processing and analysis procedures that have been tested on a range of engines and faults.

Various fault specific signal characteristics have been identified, however, as with all engine monitoring technology, the full range of engine faults has not yet been monitored. An important requirement of the processing and data analysis algorithms is the ability to evolve and develop new diagnostics as new faults are monitored. Where possible a generic approach to fault diagnostics has been used, so that the library of monitored faults is generally applicable to any type of gas turbine engine.

The analysis and processing software is implemented based on an object oriented approach. For the SFET, this is implemented on a Data Management PC, which also includes ground support station functionality. The application of the technology to different engines and installations requires different levels of integration of the technology. For example, in some applications it is a requirement to integrate the EHM processing software into an existing avionics unit, either the Engine Monitoring System or the Electronic Engine Control Unit. In other applications the integration may be at card level, it has therefore been considered important that the implementation is as flexible as possible.

The airborne processing includes data acquisition and real time processing of the EDMS signal together with the engine signals. The data is compressed and stored so that information can be reported to the ground or maintenance crew. EDMS provides early warning, so it is currently considered that the information is required at the maintenance rather than pilot level. The current implementation includes some functionality on a ground support station, for the trending and diagnostic functions.

IDMS

This section provides a brief overview of the IDMS technology, including implementation. Further information is presented in References [2] and [3].

Overview of Functionality—The Ingested Debris Monitoring System (IDMS) is based on the same principles as EDMS, i.e. the detection of electrostatically charged debris in the engine intake. IDMS monitors the electrostatic charge of the intake air and debris, either single objects or particulate material such as dust or sand, ingested into the engine.

The aero-engine is open to ingest a wide range of material, mostly non-damaging, for example insects and leaves, and damaging, for example pebbles and rivets. It is therefore important that any system that monitors for ingested material has the capability to discriminate between non-damaging and damaging debris. The correlation of IDMS data with EDMS and other engine data plays an important part in this process. This is explained in more detail below.

The early warning requirement of PHM necessitates that ingested material that is potentially damaging should be detected so that consequential damage can be minimised and remedial action taken as appropriate. In addition it may be possible to highlight that there is a high rate of ingestion during certain aircraft operating situations, in some cases it may be appropriate to change the operating scenarios to minimise the occurrence of ingestions. For example, in the military environment, streamed aircraft take-offs, with short distances between each aircraft during taxi and take-off: it may be that by extending the distance between aircraft during ground operations the rate of ingestions can be decreased.

Correlation of IDMS data with EDMS and other engine and/or monitoring data provides an improved 'picture' of the consequences of the ingestion. The first objective is to discriminate the damaging from non-damaging debris. Using correlation with other data also enables the following to be determined:

(i) Identification whether the debris travelled through the core or by-pass – there is a significant difference between the possible damage and maintenance required.
(ii) Whether the ingested material caused immediate damage to gas path components.
(iii) Whether the ingestion caused the engine to surge.
(iv) Whether the ingested material lodged in the engine.

The goals of effective monitoring and prognostic capability may also be enhanced by using the 'early warning' provided by IDMS to initiate additional, more complex processing of other monitoring system data. The overall processing requirement for the engine health monitoring system may be optimised by taking this approach for a range of sensors and technology.

Implementation—The IDMS implementation is briefly described below (see also Figure 1):

IDMS Engine Mounted Equipment

Two IDMS sensors are installed in the intake of the engine. As with EDMS the sensors are passive, however the material and design of the IDMS sensors is different from EDMS. The current sensor design is based on using flight approved tapes, installed as a ring per sensor in the intake. The sensors are axially spaced with one as close to the front of the engine as possible. A schematic of a typical sensor installation is shown in Figure 3. Sensors of the current design and construction have been installed in two aircraft intakes and flight tested to test robustness and durability. To date more than 50,000 installed hours have been accrued with several thousand flight hours.

The sensors may be integrated into the intake construction for future applications.

The sensors monitor electrostatic charge, the charge signals are converted to voltage signals using signal conditioning electronics. Similar options to those for EDMS for the signal conditioner electronics are being evaluated.

IDMS Signal Processing and Signal Processor Equipment

The signal processing and analysis techniques have been developed from research and development activities and seeded fault tests. This technology is not as mature as EDMS as the possibility for real engine ingestion tests is more restricted, the 'fault' database is therefore smaller.

The signals from the two IDMS sensors are processed to produce charge and velocity factors. This information is used with the corresponding EDMS and engine data to produce a number of factors and parameters which relate to the ingested material and its subsequent effect on the engine. The combination of factor values and settings is used to discriminate whether the material is potentially damaging or non-damaging. Analysis of the EDMS data also provides indication of the passage of the debris through the engine, i.e. by-pass or core. In some cases an additional sensor is required to achieve this, depending on the engine geometry.

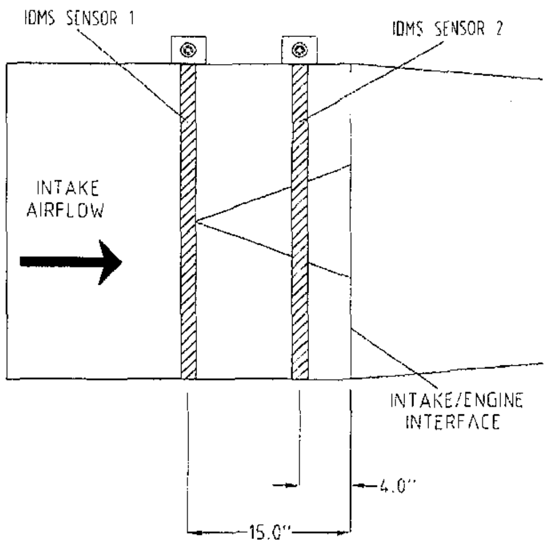

Figure 3 Schematic of IDMS Sensor Installation

Processing also identifies whether particulate material is being ingested, this is correlated with the EDMS data to assess the effect of the ingested material.

Implementation of the processing for IDMS is based on similar concepts as the EDMS processing.

Oil Monitoring

This section provides an overview of the oil monitoring technology, including current implementation. Further information is presented in References [4] to [6].

Overview of Functionality—Electrostatic oil monitoring technology is being developed primarily to address gaps in existing oil monitoring systems and therefore improve the overall integrity of oil monitoring. The main benefit of electrostatic monitoring is that it is sensitive to the earliest symptoms of oil system component degradation.

Wear-site sensor (WSS)

Development work has shown that an increase in electrostatic charge may be generated in advance of significant wear debris [4]. The physical reason for these charge generation events is still under investigation but preliminary indications are that they relate to a pre-wear, phase transformation condition existing locally on the component surface. The effect has been termed the *precursor* effect. Monitoring of this effect has potential for giving advance warning of oil system component deterioration and hence providing the early prognosis required for total PHM.

Based upon the precursor effect, a wear-site sensor (WSS) system has been developed for monitoring specific oil components. Results from tests of this system on a gearbox are reported in Reference [5]. The WSS may also be used for monitoring vulnerable components where the time from onset of deterioration to catastrophic failure is typically short (of the order of hours) and for which an early warning of impending failure is important. This is paramount when failure results in substantial secondary damage such as loss of machinery or even life.

As the WSS is sensitive to early or pre-wear conditions, it has potential for aircraft pre-maintenance operational guidance. For example, if a developing engine fault is exacerbated by running at certain power levels, then it may be feasible to use the WSS output to determine the engine power levels which minimise the risk of rapid deterioration to failure. This could have significant benefit in terms of returning aircraft to main base for repair, rather than unserviceable engines (or even aircraft) requiring transportation from down-line.

Oil-Line Sensor (OLS)

For a number of oil wetted components, fine particulate are predominantly generated during the early stages of component wear and hence, if monitored, may be used as the basis of oil system prognostics.

More recent developments, particularly for high speed aircraft engine bearings, have led to the use of exotic materials and ceramic coatings. If such components are to be introduced for modern engines, then there is a requirement for monitoring non-metallic wear debris.

On this basis, existing in-line oil debris monitoring devices have two significant limitations, namely insensitivity to fine debris and the inability to detect non-metallic particulate. The OLS system is being developed primarily to address these deficiencies. Since the electrostatic sensor detects the charge carried by the debris then there is considerable scope for the nature of the debris which may be detected. Earlier tests on a gearbox rig showed that the OLS is sensitive to sub 50 μm debris. This was corroborated with results from slide particle analysis [6]. In principle, this system could also be applied to detection of sand contamination in oil systems.

Lubrication deterioration increases the conductivity of oil which, in turn, will influence the background charge levels. It is feasible that this global change in the oil, due to lubrication deterioration, may also be detected by the OLS system.

Implementation—For the first SFET, the electrostatic oil monitoring equipment comprised sensors, charge amplifiers, a Personal Computer and Digital Audio Tape (DAT) recorder, as illustrated in Figure 4. These elements and signal processing methods are described below.

Unlike EDMS and IDMS, the electrostatic oil monitoring systems had not been tested on an engine before and so the equipment used during the SFET was experimental. The equipment design has not been finalised for an engine or aircraft application, so one of the objectives of these tests was to understand and survive the engine environment. Generally, the system performance was satisfactory although the OLS have been modified for the second SFET.

Oil Monitoring Engine Mounted Equipment

Both types of electrostatic oil monitoring systems were fitted to the engine:

(i) WSS: A small discrete button sensor located in the vicinity of a specific component, intended to monitor degradation of that component. WSS were installed in the No. 1 and No. 5 bearing chambers.
(ii) OLS: A dual element ring sensor which is mounted in the oil-line to monitor for changes in the oil system. OLS were installed in No. 1 and No. 5 bearing oil scavenge lines.

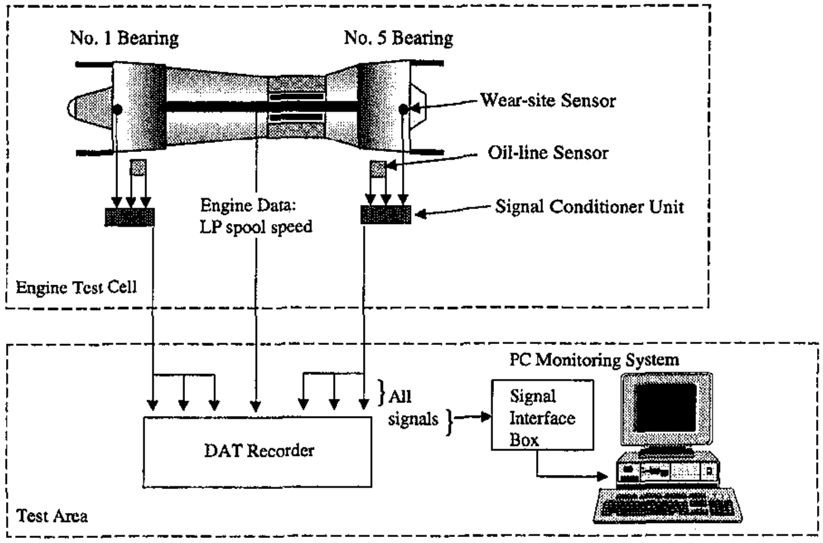

Figure 4 Schematic of the Electrostatic Oil Monitoring Equipment

A schematic of the number No. 1 bearing WSS and OLS installations is given in Figure 5.

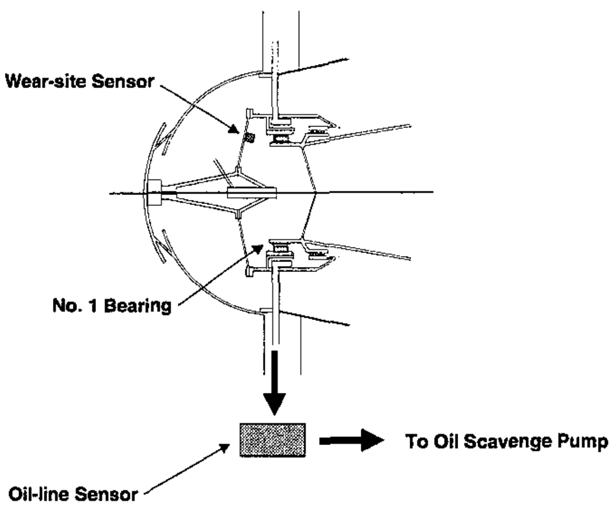

Figure 5 Schematic of the No. 1 Bearing WSS and OLS Installation

The sensors are passive devices which detect changes in the electrostatic charge level. Changes in the charge level may be due to debris production, oil contamination, changes in the oil condition or contact surface modification relating to the onset of component wear. All sensors are mounted in-line so that signals may be processed to provide a real-time analysis.

A charge amplifier was used to condition the electrostatic charge signal from the sensor. The unit converts the charge signal to a voltage signal suitable for acquisition and processing.

Oil Monitoring Signal Processing

The signals were monitored in real-time using a PC based data acquisition system. This enabled a basic assessment of the electrostatic sensor data to be undertaken during the engine tests. The signals from the charge amplifier were also recorded on DAT for post test analysis and further development.

- Wear-Site monitoring

The WSS views a whole host of charge signals in the bearing chamber, relating to lubrication being sprayed in and out of the bearing and distributed around the chamber, as well as signals due to the operation and condition of the bearing.

Component degradation initiates with breakdown of a contacting surface. Typically this may be caused by poor lubrication, small defects in the surface material or the addition of foreign particulate. Localised phase transformation of the component surface results in increased charge levels being generated as the weakening surface is worked by the contact. For a bearing, it is possible to calculate the frequency of the increased charge signal associated with a given element being damaged. Thus specific information about the bearing can be achieved by processing charge signals in a way that the relevant information is highlighted and the background effects can be disregarded. This is the basis of the approach used for the WSS data analysis.

Frequencies relating to No 1 and No 5 bearing defects – outer race, inner race, rolling element or cage - are deduced from the engine low pressure (LP) spool speed. The electrostatic sensor signal content is analysed for these frequency components and an assessment of the bearing condition made. The SFET data provides an opportunity to assess and refine the WSS signal analysis.

- Oil-Line Monitoring

The OLS senses the oil and associated properties in the oil-line. It produces two output signals which are used to deduce velocity information related to the oil flow. Signal levels are averaged and combined with the velocity data to produce a series of indicators. The basis of the analysis is to determine the indicator characteristics associated with 'good' oil system condition and look for subsequent changes in this.

The SFET data is intended to assess and improve the performance of these OLS system indicators.

3. Seeded Fault Engine Tests

The main objective of the seeded fault engine tests is to produce realistic engine fault data to enable testing and development of the prognostic capability of each technology. This paper addresses results from the first SFET.

The first SFET included gas path component deterioration, objects ingested into the engine and various oil system defects such as bearing damage and oil degradation. The results from each EHM system is briefly assessed against the relevant seeded fault and, where applicable, corroborative engine data.

Gas Path Component Deterioration and Faults – EDMS Results

Several faults were seeded in the gas path during SFET #1, most of these are considered to be representative of the fault condition at an early stage and therefore establish the early detection requirement necessary for the PHM concept.

A summary of some of the seeded faults and an assessment of the detection capability of EDMS for these faults is described below and in Table 1.

Bowed Rotor Start—A bowed rotor start was induced, which resulted in high pressure compressor rubbing during an engine start to idle. EDMS activity level and shaft order components showed significant changes compared to the datum for the healthy engine. The combination of the indicators confirms that the bowed rotor start occurred during the acceleration to idle.

These results indicate that rubbing occurred on the HP spool during the start, with some evidence of rubbing on the LP spool as well. The data shows that the maximum effect occurred at approximately 25% N1 (LP spool) speed and that the rubbing produced fine debris.

Gas Generator Uptrim—The gas generator uptrim test was achieved by altering the engine control unit, to provide variation in the fuel flow and temperature, at the high power condition.

The EDMS data for this test shows a change in the activity level parameter at the high power condition compared to the datum healthy engine. PHM requires that diagnostic information is available, in preference to "a change from the normal." This type of fault has not been monitored before by EDMS, the following is an example of the logic that may be used to initiate the diagnostic process:

The shaft order analysis data for this test does not show any differences at 100% compared to the datum engine data. This indicates that the increased activity level is not related to rubbing. Other faults that may show a similar effect at maximum spool speed include burning and nozzle guide vane (NGV) erosion. In previous engine tests on other engines NGV erosion and burning have been monitored and have started to occur before maximum spool speed, this may enable some level of diagnostic capability to be determined from the EDMS data. Correlation with the spool speed and temperature should provide an enhanced diagnostic capability.

Table 1 Summary of EDMS results from SFET #1

Seeded Fault	Monitoring system observations	SFET result
Bowed rotor start	Increase in HP spool, LP spool shaft order levels Activity level increase Maximum effect at 25% N1	Rub occurred during engine accel to idle (43% N1)
Gas generator uptrim	Change in activity level at high power No change in shaft order	Engine performance changed at high power condition
LPT3 & 4 rubs during transient engine operation	Increase in activity level during accels (finer debris) Increase in events at snaps (larger particulate)	
A/B gutter damage/liberation during A/B cycles	Activity level and event rates increase at start of 3rd cycle	Inspection confirmed that gutter liberated
Blocked fuel nozzle	Effect detected at 9200 rpm	

Low Pressure Turbine (LPT) Rubs—Blade rubs were simulated on LPT3 and LPT4, these were of very short duration during an engine transient condition. In both cases the tests included accels between idle and intermediate, a short period of running at intermediate, snap to idle and short dwell time at idle followed by a snap to intermediate. It was thought that the rubs would occur during the snaps to intermediate. The EDMS data indicates that some rubbing occurred during the accels in both cases, shown by higher than normal activity level during the accel with a residual effect during the snap shown by the event rate parameter. The activity level parameter tends to be indicative of finer debris and when produced during a rub is usually due to gradual contact between the blade and casing, for example due to increased centrifugal force. The event rate parameter tends to indicate larger debris and when produced during a rub is usually due to relatively large impacts between the blades and casing, this is likely to occur during the snap.

Afterburner Gutter Damage Liberation—The afterburner (A/B) gutter was damaged in 2 places and the engine run for several cycles between military (ie with full A/B) and max dry powers. The data shows that during the 3rd cycle the activity level and event rates increase at one point compared to any other data at A/B operation during the run. The combination of the indicators from these parameters suggests that the damaged section of A/B gutter was liberated at this time, this was confirmed by post test inspection.

Blocked Fuel Nozzles—This test was carried out at several engine operating conditions, with the intention of identifying at what point the fault would become 'visible' to EDMS. The EDMS data only appeared to show any effect at 9200 rpm, the highest operating condition for which data has been acquired to date.

Further tests will be carried out during the second SFET to investigate this fault and the effect on EDMS.

Ingestion Tests

The data from the ingestion tests and general engine operation during the first SFET have been reviewed.

Objectives—The objectives of the review are:

(i) Confirm that IDMS and/or EDMS detect objects successfully seeded into the engine intake.
(ii) Confirm that the discrimination algorithms and thresholds implemented result in the correct classification of the debris as either damaging or non-damaging.
(iii) Review the false alarm rate achieved during the tests.

IDMS Results—The IDMS diagnostics identifies Categories for the detected debris. Debris which results in Category (Cat) 0 is classified as non-damaging and Cat 2 is classified as damaging. A Cat 1 classification is also used: this category is used where the calculated factors and flags are not within the threshold band ranges currently used for the classification. The number of ingestions classified in this category is reducing as the database and experience increases.

Although most of the seeded ingestions are considered non-damaging the results show that the classification analysis results in the correct category classification. The ice ingestion results in Cat 1 classification, possibly damaging, the classification should be Cat 2: Alternative threshold and factor combinations are being reviewed and will be applied during SFET #2.

Correlation between the EDMS and IDMS data is an important part of the processing and significantly improved the classification of ingested debris to minimise false alarms.

False Alarm Rate—One of the key requirements of monitoring systems is a low false alarm rate. As the engine can ingest both damaging and non-damaging debris it is important that non-damaging debris is correctly discriminated and not reported in an operational scenario. The IDMS monitoring and analysis was set up to detect any ingestions so that the false alarm characteristics of the system could be checked.

Ingestions were monitored during nearly all periods of engine running. These were thought to be mainly due to insects, confirmed whenever the intake was rolled back as the front fan always showed the evidence – dead insects on the blades. The ingestions monitored during each test were classified to confirm that correct discrimination was achieved. Typically between 10 and 90 ingestions were detected per period of engine running, some of these were the seeded debris, generally these were insects. The ingestion events for all tests have been classified. There are a few occasions where a classification of Cat 1 results, it has been assumed that no damaging debris was ingested into the engine except for the seeded ingestions, therefore these should be considered as false alarms. The classification of the monitored ingested foreign objects, including insects etc. does not result in any Cat 2 false alarms. Based on the results to date the false alarm rate is low. A full assessment will be carried out after the second set of engine tests.

Oil System Faults

Oil system faults relevant to the electrostatic oil monitoring were those seeded in No. 1 and No. 5 bearings and the oil degradation test. The seeded faults and propagation are briefly described together with the preliminary assessment of the oil monitoring data. The main aim is to use the first SFET data to test and refine the electrostatic oil monitoring system. The test results are summarised in Table 2.

No. 1 Bearing Defect—Prior to the start of the first SFET, the No. 1 bearing inner race (IR) was heated and pre-marked with indents. During testing, bearing rollers were removed and oil starvation to No. 1 bearing chamber undertaken in an attempt to promote bearing distress. On the final day of engine running significant particulate contamination was injected into the bearing and race cavity and the bearing run 'dry'. This final act caused significant damage to the bearing.

At the start of the first SFET, the IR defect frequency was monitored by the bearing No. 1 WSS. Slip associated with the lightly loaded bearing was in the region of 10%. As testing progressed, the charge levels associated with the IR damage reduced. This indicated that the seeded race damage may have been healing, which is consistent with a softened inner race being susceptible to 'smearing' of the damage sites. Inspection of the bearing after this period of testing showed no significant propagation of the fault.

Further testing with half the rollers removed and oil starvation resulted in different WSS signal characteristics. When the bearing was lubricated a relatively strong tone at 'half rollers' defect frequency was, on occasion, evident. However, whilst loss of lubrication is very evident in the WSS signals, oil is important for monitoring bearing generated charge within the chamber.

The effect of contamination debris injected into the bearing chamber was very apparent from the WSS data. Debris was monitored by the WSS for more than 10 minutes. It is very likely that significant bearing damage occurred during this period. The effect was fairly random in the frequency analysis because the debris and / or the nature of the bearing damage cannot be related to one specific bearing entity.

Before this stage of the SFET, no debris had been liberated by the No. 1 bearing. Although the contamination debris was added during the oil starvation period, because the scavenge pump was still running, the contamination and bearing generated debris were sucked through the OLS. The effect of this on the OLS system was very significant when compared to rest of the testing. Debris was monitored by the OLS for more than an hour.

In summary, the No. 1 bearing IR defect was seen by the WSS sensor. However, the nature of the seeded fault testing (in particular removal of 10 rollers and prolonged periods of oil starvation) plus the influence of bearing slip, lead to difficulties in separating these effects in the WSS frequency data. The contamination debris and its effects were monitored by both the OLS and the WSS over a significant period of time.

No. 5 Bearing Defect—Number 5 bearing was pre-damaged by heating up the inner race - no indents were made.

Bearing No. 5 WSS signal exhibited different characteristics to bearing No. 1. No. 5 bearing WSS data did not show any defect frequencies related to specific damage. The power spectra (frequency) data remained consistent throughout the tests, indicating that the initial bearing damage did not propagate during the engine running. This was confirmed by post-test inspection of the bearing.

Oil Degradation Tests—The oil degradation phase took place over several days. The oil was heated to temperatures in excess of 400°F and the oil condition sampled and analysed at various times.

As the oil condition degraded, the global effect of this on the OLS background signal level was evident.

4. CONCLUSIONS

Potential EHM technologies for the JSF PHM program have been tested during the first SFET. This paper has reviewed the results from three such technologies, namely EDMS, IDMS and the oil monitoring (WSS, OLS) systems. The various engine faults included gas path component deterioration, foreign object ingestion and oil / component degradation. Most of the faults were incipient in nature and so required early detection and subsequent monitoring. The tests enabled the capability of each EHM system for timely detection of the relevant seeded faults and fault tracking to be demonstrated. Where available the EHM fault prognosis / diagnosis was corroborated with subsequent engine inspection data.

Table 2 Summary of oil monitoring results from SFET#1

Seeded Fault	Oil monitoring sensor	Monitoring system observations	SFET result
No. 1 bearing, IR annealed and indented	WSS1	IR defect frequency monitored (10% slip). Defect signal level reduced as testing progressed.	Bearing removed and inspected. No evidence of IR fault propagation. Possibility of IR indents smearing / repairing.
No. 1 bearing, 10 (out of 20) rollers removed	WSS1	Small '10 roller' defect frequency - level not as significant as at start of SFET#1.	
No. 1 bearing, oil starvation	WSS1, OLS1	WSS signal diminished. No signal on OLS.	No oil through bearing chamber or oil line.
No. 1 bearing, contamination debris added & oil starvation	WSS1, OLS1	High level, random frequency signal on WSS1 Very large signals caused by debris passing through OLS1	Significant debris liberated from bearing during this period
No. 5 bearing IR annealed	WSS5	No change in sensor data throughout testing.	Bearing inspected at end of test. No fault propagation observed.
Engine oil heated in excess of 400°F	OLS1&5	RMS levels change significantly during period of hot oil runs.	Severe oil degradation occurred during hot oil runs.

The broad requirements to progress EHM towards total PHM have been discussed and certain aspects highlighted with respect to the described technologies. In particular, it has been demonstrated that integration of IDMS, EDMS and engine data is beneficial to FO detection, discrimination and subsequent engine damage, thereby significantly improving system performance.

The first SFET provided an opportunity to test the functionality and maturity of the EHM technologies described herein. Additionally, it has been demonstrated that, as the technologies are exposed to new or different faults, diagnostics can be developed and equipment revised in order to improve the effectiveness and efficiency of each system. For the OLS and WSS systems, the SFET enabled the technology to be tested on an engine for the first time. The tests provided valuable experience regarding the engine environment and have resulted in development of the OLS for the second SFET.

Diagnostic and prognostic capabilities will be further tested during the second SFET, which will provide the opportunity for detection of different seeded faults and for monitoring fault progression.

5. References

[1] Powrie H.E.G. and McNicholas K., "Gas Path Condition Monitoring During Accelerated Mission Testing of a Demonstrator Engine," AIAA Paper 97-2904, July 1997.

[2] Nurse J., Petch C. and Fisher C.E., "Engine Gas Path Integrity Monitoring," *Aerotech 94*, Paper C470/6/052, January 1994.

[3] Barnes O.R.J., "Report into Progress in the Development of the Stewart Hughes Limited Foreign Object Detection System using the Ingested Debris Monitoring System (IDMS) and the Engine Distress Monitoring System (EDMS)," MoD Report LC/165116/2/7/2/1/ Logs(OR), December 1996.

[4] Tasbaz O.D., Wood R.J.K., Browne M., Powrie H.E.G. and Denuault G., "Electrostatic Monitoring of Oil Lubricated Sliding Point Contacts for Early Detection of Scuffing," accepted for publication in *Wear Journal*, November 1998.

[5] Powrie H.E.G., Tasbaz O.D., Wood R.J.K. and Fisher C.E., "Performance of an Electrostatic Monitoring System During FZG Gear Scuffing Tests," *International Conference on Condition Monitoring*, University of Wales Swansea, UK, April 12 – 16, 1999.

[6] Powrie H.E.G. and Tasbaz O.D., "Investigation into Use of Electrostatic Monitoring in Oil for Early Detection of System Degradation," Stewart Hughes Limited Report No. SHL1344(1), February 1998.

6. Acknowledgements

This work has been carried out with the support of the US DoD (JSF PHM Program Office), Pratt & Whitney, Florida and Stewart Hughes Limited (UK).

The authors also wish to thank Mr Bob Tape of ExperTech Inc. for his assistance with equipment installation and support during the seeded fault engine tests.