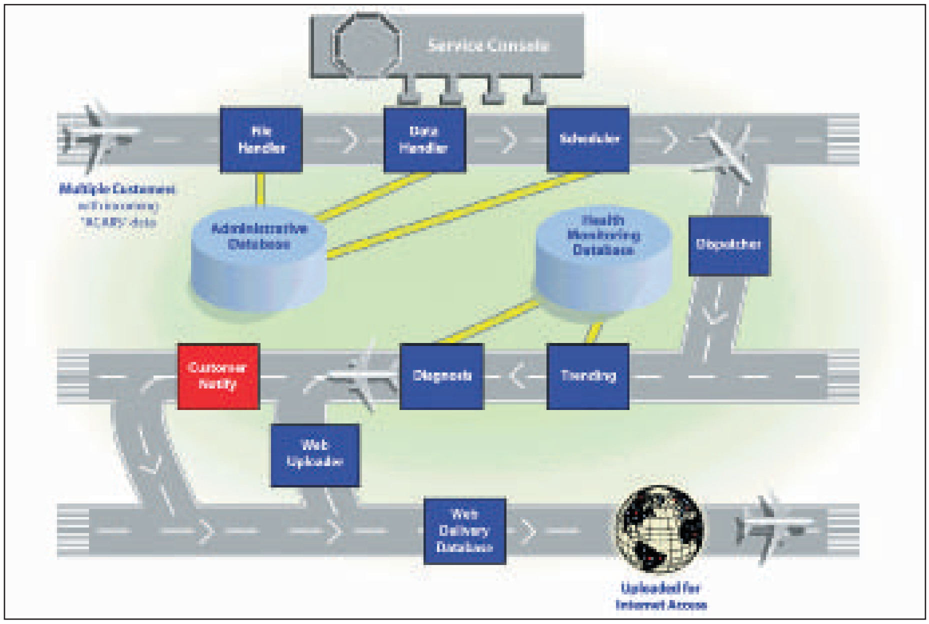
Are your engines really as healthy as they seem?

It is a simple fact that most engine health monitoring (EHM) systems used by airlines are unsuitable for the job. Why? Because they fail to solve the automation dilemma - on the one hand businesses want cost reductions, but on the other, high quality health monitoring demands some degree of human judgement. In this article, Data Systems & Solutions (DS&S) discusses how it solved this dilemma with its EHM solution, which is now used to monitor more than 4,000 engines.



Currently, EHM quality is normally judged on the fairly rudimentary basis of 'alerts' - the number of genuine alerts missed or misdiagnosed, together with the number of spurious ones delivered. With its solution, DS&S is already at a level of maturity where it is extremely rare for an alert to be missed, or for instances of a particular fault to be incorrectly diagnosed. Furthermore, spurious alerts - those resulting from normal scatter in the data - are virtually eliminated. This being the case, if EHM alerting and diagnosis is to advance still further, a paradigm shift in the diagnostic system installed on the engine will be needed. Such a shift will take place when the 'QUICK' analysis technology being developed by Rolls-Royce enters service on all A380 aircraft in less than two years time.

In the meantime, in order to enhance the benefits of EHM on today's engines, DS&S is applying significant research and development resources to create new computing techniques designed to solve difficult pattern recognition, diagnostic and forecasting problems. It is also working with maintenance management systems providers to develop advanced asset management capabilities that will capitalise on its existing diagnostic and forecasting technology. In fact, DS&S has recently completed major programmes of research into improved engine modelling and diagnostic techniques, which are already embodied in its existing EHM service system.

Adding the X-factor — eXperience

The key characteristic of DS&S' EHM service system is that it is capable of continuous, fully automatic operation, whilst allowing manual intervention in the case of a specific alert and when system training is required. It has been operational since early 2003, and already processes an estimated 10,000 health monitoring 'snapshot' reports per day.

The main features of the system are:

- high integrity;
- near real-time operation;
- full end-to-end automation;
- the system is 'data-driven' — the system starts in response to data arriving;
- automatic adherence to the specific business rules of each organisation;
- flexible data input;
- absolute segregation of data for each customer;
- complete audit trail of the data-processing cycle;
- it is easily scaleable, without software change;
- central control; and
- access using commonly-available web-browsing tools.

The EHM system's modular design allows functionality to be hosted on one server or to be distributed across a number of servers, so that it can be "grown" smoothly to manage any number of engines simply by adding more modules onto existing or additional servers. The system's inherent flexibility also means that it

Rolls-Royce takes EHM technology into the 21st century

The Rolls-Royce QUICK system, developed in association with Oxford University, is an advanced engine vibration analysis system based on that used in Rolls-Royce's engine test facilities. Rolls-Royce is developing an on-engine version of the system for the Trent 900 engine for the Airbus A380 aircraft, which will be available for retrofit to other Trent engines.

The engine mounted QUICK unit continuously monitors engine rpm, vibration and other signals to give early warning of problems and accurate diagnostic information. QUICK's advanced signal processing and neural network techniques extract the maximum amount of information from vibration and other sensors fitted to an engine to identify anomalous behaviour and generate fault diagnoses. These diagnoses are compared with a database of known conditions and then transmitted to the ground for analysis and action. The initial database is generated using test-bed data and is updated with knowledge acquired in service.

DS&S is working with Rolls-Royce to seamlessly integrate the additional information available from QUICK into its EHM system in time for the entry into service of the Trent 900 in early 2006.

can be used on aircraft and aircraft system applications (such as APUs). It can also be used in non-aerospace environments such as utilities, railways and marine applications.

Taking control of your business

At the heart of DS&S' EHM system is the administrative database, which holds the business rules specific to each organisation. These rules determine the priority in which data will be processed, the details of the processing to be performed, the destinations of the various forms of output and so on.

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The progress of each file is tracked at every stage and if processing is interrupted for any reason it can be restarted with no loss of data. System performance can also be monitored from the individual file level to that of the whole system, whereby statistics such as average end-to-end processing time can be obtained.

The console module provides system supervision functions, so the status of the system can be monitored, individual files can be tracked and information on particular airlines or fleets can be reviewed (such as time of last data receipt, when a particular aircraft last sent data, and so on) or it can be used to review processing errors.

While the EHM system is designed to operate with minimal supervision, it must be kept running at all times to prevent backlogs, and data should not be discarded indiscriminately. To overcome any possible conflict in these directives the system is designed to actively alert the system supervisor of impending problems such as 'bad data' or the failure of a system module to start, via an automatic e-mail alert. The supervisor can then log in, remotely if necessary, to perform the required remedial action.

Turning data into decisions...

One of the most significant challenges for any health monitoring system is the fact that data files can be sent by airlines in a number of formats and by different means of transmission. For example, most files arrive at the gateway to the system as e-mail or an FTP transmission, in ASCII format or a compressed form. So, DS&S' EHM solution includes e-mail and FTP file-handlers, which will accept the incoming data according to the method of transmission. Upon receipt of the incoming communication, the file-handler automatically determines how the data is being carried (embedded, attached, compressed, whatever) and converts it into a data file. It also records the identity of the data sender.

The files are subsequently passed to the data-handler module where their contents are read. The data-handler can perform operations on the data such as patching known errors (a report may have no year or date specified), according to the business rules in place for each airline and fleet. It may also link or split data files, as required, to optimise processing.

At this point, the system understands what needs to be done with the incoming data, and the 'job' is passed on to the scheduler module, where it is placed in a queue. The scheduler assesses the resources available and queues the jobs to ensure that customer service-level agreements are complied with. If a large quantity of data arrives in a short time, the scheduler determines the best strategy to minimise service-level deviations and it can look ahead to predict how the queue is likely to progress. This queue prediction can be viewed via the console.

... and decisions into actions

Once the queue of jobs has been defined by the EHM system's scheduler, the dispatcher module executes them using the system's trending and computational intelligence (CI) tools to identify likely causes and solutions. Specifically, the trending tool, which is a version of DS&S' engine monitoring system COMPASS Navigator™, normalises the observed data for any variation in operating conditions and compares it to an engine performance model, thereby providing optimum trending information on engine condition.

In parallel, the CI tool performs three main functions: it cleans any systematic errors from the trended output; identifies any anomalies in the data; and ascribes a diagnosis to anomalies that are found. As such, the development of the CI tool has proved to be an essential enabler to the cost effective delivery of a 24/7 engine health monitoring service since previously all trend inspections had to be performed manually. In addition, the CI tool has the capability to manage multi-parameter alerting, which is a significant step forward from traditional single-parameter alerting used in most EHM systems. Refining the detection techniques employed and combining the information from a number of related parameters vastly increases the probability of correctly identifying impending problems. For example, a deviation in a single parameter is most likely to result from a sensor problem, but consistent deviations in a number of related parameters would be indicative of a genuine engine fault.

As a final step in the management process, the EHM system's 'web uploader' module uploads newly processed trend and alert data to the web database for access by authorised personnel through CoreControl™, DS&S' predictive services web portal. In addition, if an alert has been generated the 'customer notify' module will send a notification by e-mail or SMS text message. Typically, the entire health monitoring process takes less than 10 minutes from receipt of incoming data to updated trends being available to the customer.

A question of technique

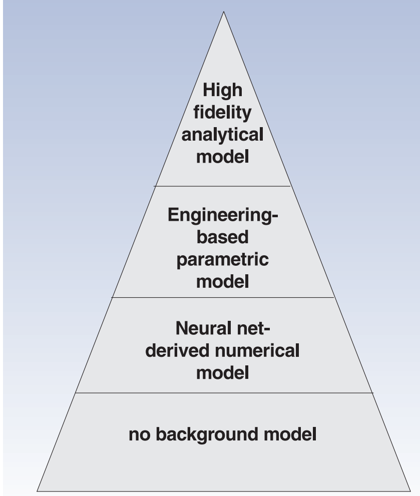
DS&S' approach to EHM is based on the use of a number of techniques to trend equipment parameters, but to ensure the most reliable results, it will always default to using the one that is highest in the accepted hierarchy of trending techniques (see figure 2).

Ideally, all monitored engine parameters that vary in a prescribed way relative to a set of independent variables should be compared to a background model. For example, engine gas path parameters vary depending on engine thrust setting, altitude, airspeed, total inlet air temperature and other independent parameters. Gas-path parameters should, therefore, be trended relative to a model that embodies their relationship with the independent variables.

However, some monitored parameters, such as broadband and tracked order vibration signals, have a very weak relationship or none whatsoever. In such cases, a background model is of minimal benefit, and the parameter would be trended 'raw', or monitored relative to a constant reference value.

Where high fidelity analytical models are available or can be created from knowledge of the way that equipment works they represent the best quality trending solution. These models have a known validity range and provide a basis for further analysis and understanding of the problem when an anomaly has been detected. However, if these models need to be created specifically for trending work, such a solution can also be the most expensive.

Where no analytical model is available, engineering-based parametric models can be created from observed performance data, together with a general



understanding of engine performance. These models exhibit linear behaviour outside their derivation domain and provide some level of understanding of the anomaly detected. DS&S has recently completed a research and development project to create a rapid method of producing models of this type for any engine.

Where there is no engineering understanding of the operation of a piece of equipment and the manufacturer is therefore unable to supply a model of it, the only recourse is to derive a numerical model. DS&S uses computational intelligence techniques, such as neural networks, to create this type of model - usually for monitoring of equipment other than gas turbines. As a primary trending technique, the models are generally good within their training domain, but tend to exhibit unpredictable behaviour when a new set of operating conditions is encountered and the model is unable to suggest a reason for the detected anomaly.

Why it pays to be a model worker

Rather than working at an individual engine level, DS&S' EHM system is designed to use one trending model to represent each distinct 'bill of material' or 'model' of an engine. Provided the quality of the model is shown to be satisfactory,

this approach permits the same model to be retained indefinitely, unless there is a significant change in the engine design, such as a major performance-improvement modification.

This approach yields a number of advantages relative to individual engine serial-number-based modelling. Remodelling is rarely required but even where it is, it will normally be to implement improvements to reduce trending scatter, so the main datum level will be retained. This ensures that long-term changes are detected, proximity to physical limits exposed and engine-to-engine and fleet-wide comparisons are sound. Consequently, health monitoring is firmly grounded on a view of how the equipment is behaving relative to the design intent.

In comparison, other modelling methods tend to centre on a view of how engine health has changed since the beginning of monitoring, which unfortunately makes the false assumption that the engine was exhibiting satisfactory or 'normal' operation during the initial model-building period.

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Now with added intelligence

DS&S identified the value of computational intelligence techniques at an early stage. As a result, most of its current services use a high-fidelity analytical or parametric model as the primary trending technique, with a computational intelligence model as a secondary 'line of defence'. This means that maximum understanding and linearity is extracted in the primary trending and further extraction of unaccounted-for systematic relations is achieved in the secondary trending. In this way, the strengths of both approaches are cumulative, maximising the probability of finding and correctly diagnosing a fault.

Within DS&S' EHM system, the computational intelligence tool uses a secondary neural-net, multi-layer 'perceptron' model to remove any remaining systematic errors in the trend data following application of the primary model. Use of this two-phase approach leads to the smoothest possible trends, so that anomalies in the data are identified with greater reliability. The neural-net model is derived off-line from the service, using data from a number of engines.

Having smoothed the trends, the CI tool uses an improved Kalman smoothing technique to fit the trend data and reject outliers. Based on the resulting fit, the software detects anomalous data according to predefined criteria. The anomaly will be defined in terms of deviations in a number of parameters as well as their rates of change and cumulative change.

The anomalies detected are then passed to the diagnosis section where they are compared with the knowledge base of known diagnoses. The CI tool determines goodness of fit with the known events and ranks them in order of likelihood. Diagnoses are then either "remembered", if they are below the alerting threshold, or made available to the 'customer notify' module of the EHM system, to generate an alert.

Closure of alerts (and the health monitoring process) is achieved by feedback through the CoreControl™ web portal. Generally the airline will determine when the alert is closed, though in some cases this responsibility lies with the engine manufacturer, especially if the engine is on a 'power-by-the-hour' maintenance contract. DS&S' back-office procedures and software ensure that the maximum value is derived from each alert in terms of 'training' the EHM system to detect the same problem as soon as possible the next time it arises and providing the best possible diagnosis for each feature detected.

EHM in action

Allowing an aircraft to keep generating revenue is one of the most valuable benefits of EHM, as demonstrated by a recent in-service event with a Rolls-Royce Trent 500-powered A340.

Following a lightning strike, the aircraft experienced surge messages during the climb phase en-route across the Pacific. The Rolls-Royce operations room was notified of the incident by DS&S' health monitoring systems and the relevant technical data was made available to support a rapid decision on the necessary course of action.

A technical variance was subsequently issued to waive the borescope requirements (no defects were found when the engine was inspected four days later) and the necessary people, information and approvals were all in place to meet the aircraft on its arrival. Consequently, thanks to the fast and effective decision-making enabled by the EHM system, the aircraft was immediately able to turn around and continue on its return journey.

Realising the benefits

Thanks to its advanced knowledge management, modelling and computational intelligence techniques, DS&S' EHM system has been proven to deliver a wide range of operational and administrative benefits, including:

Engineering

- more accurate diagnosis of problems;
- real-time alerting; access to data 24/7;
- easier maintenance contract administration;
- rapid identification of performance and reliability issues;
- improved maintenance planning; and
- reduced unplanned removal rates.

Customer service

- increased customer service levels; and
- increased revenue opportunities.

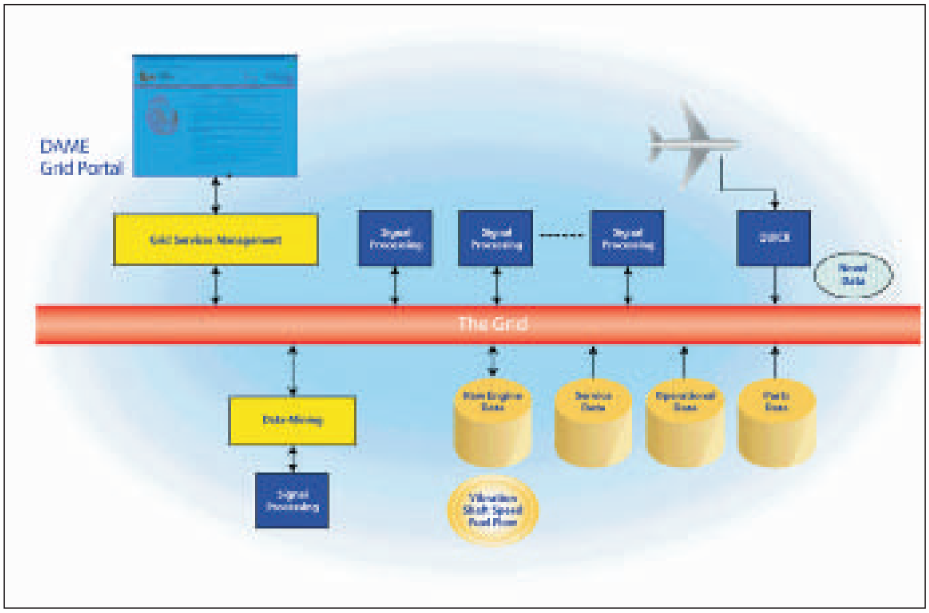
Flight operations

- enhanced safety;
- improved dispatch reliability; and
- improved crew and aircraft utilisation.

Management

- reduced operating and support costs; and
- accurate planning and forecasting.

In fact, DS&S continuously monitors the value of EHM services provided to its customer, and these have been shown to routinely deliver a return on investment of between 300 and1,000 per cent.



... and things can only get better

In the quest to deliver even greater benefits in the future, DS&S is actively involved in the distributed aircraft maintenance environment (DAME) project[1], a 'grid'-based diagnosis and prognosis system for aero-engine data (see figure 3). Grid computing utilises the free resources of a large number of high-bandwidth network-connected computers to tackle difficult computational problems in a fraction of the time that would be needed for a single computer, at a much lower cost than a dedicated multi-processor super-computer.

This £3m ($5m) project, which is co-sponsored by Rolls-Royce and Cybula Ltd is expected to finalise in 2005 and has already developed a complete pattern storage and search system, based on existing AURA search technology. To facilitate the use of this distributed system, an application specific, portal-based data browser and search interface has been developed called the signal data explorer.

The problems solved in developing a demonstration of this technology have many applications outside of the specific remit of the project and DS&S is leading the efforts to apply the technologies developed under DAME to all aspects of aero-engine monitoring, in both grid and non-grid environments, so its customers will continue to benefit from access to the world's most advanced EHM solutions. ■

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1 The details of the complete DAME project can be found in Chapter 5 of Grid 2: Blueprint for a New Computing Architecture (Second Edition); I Foster & C Kesselman (Ed), published by Elsevier/Morgan Kaufmann, 2004.