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INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

Non-Intrusive Technologies for Gas Turbine Operators

by

Jeff Bird
Brian Galeote
Tim Breithaupt
of
National Research Council
Institute for Aerospace Research
Gas Turbine Laboratory
Ottawa Ontario

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Abstract

Diagnostics for high value gas turbine machinery can benefit from new and evolving sensor technologies. Test cells and ground–based installations are seen as important targets for applications to benefit operators. In fact, such installations also offer opportunities to contribute to the development of sensor technologies. For practical applications, current work has focused on non-intrusive sensors that can be installed readily on working gas turbines- often as part of the installation and not engine-mounted. Current capabilities are surveyed to define sensing needs and appropriate technologies. Technology development and demonstration work is described for infrared, spectroscopy and electrostatic sensors, along with plans. The integration emphasis necessary for true benefits to operators is described based on related data fusion and decision support work also underway. Opportunities for the user and technology communities are discussed.

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Background

The National Research Council's Gas Turbine Laboratory has been involved in development, test and evaluation of gas turbine technologies since the 1940s. Throughout this period there has been a steady need for and emphasis on better ways of assessing engine performance and condition. NRC typically sees the range of applications from development to certification so improvements are motivated by safety and cost effectiveness: usually the test engines and/or the extensive instrumentation are unique and may be prototypes or experimental in nature.

While most laboratory work has been in a test cell environment, projects have often benefited from multi-disciplinary specialists from across NRC's institutes. For example, the Institute for National Measurement Standards has provided unique expertise and equipment for thermometry and spectroscopy and the Institute for Information Technology has been instrumental in introducing expert systems, data mining and other analysis techniques. Specialists in the Institute for Aerospace Research have participated in important tasks in projects involving, for example, combustion, performance correlation, environmental simulation, novel materials, non-destructive inspection, droplet sampling, inlet aerodynamics, and noise. Consequently specialized methods and equipment, normally used only in a laboratory setting have been assessed and often adapted for use in NRC test cells. The participation of the on-site specialists extends to involvement in test planning and evaluation of results.

NRC projects have regularly involved users with operations and maintenance (O&M) issues. Typically, limited instrumentation and capability exist to address the operator's complete needs: assess engine condition, confirm an anomaly and isolate to a component. Operator procedures and equipment have usually been designed for limited performance measurements, rapid turnaround and minimum cost rather than adaptability. The complexity and cost of current propulsion and power systems limit the test opportunities to gather information with which to make operations and maintenance decisions. Opportunities and technology developments associated with advanced technology programs like the 'intelligent' engine also focus on the need for advanced sensors for health management and distributed control (Simon et al., 2004).

Approach

Awareness of these operator issues similar to our own need to maximize test output coupled with access to diverse laboratory grade sensors has shaped a special approach to engine condition monitoring. Throughout, the emphasis is to augment the practical means to impact O&M decision-making. However, it was recognized that any changes to installations and instrumentation within the engine and components would have to be justified. Both initial cost and life cycle cost benefits would have to be convincing to justify retrofitting any special condition monitoring instruments. Access to technology demonstration engines at NRC test cells was seen as key to developing and validating sensor systems in relevant conditions. Both technology developers and users are viewed as partners in this approach.

Since the emphasis of this work is on the development of sensors to contribute to life cycle management of gas turbine systems, this report focuses on the sensor development underway at NRC, with reference to current international research and development. In addition, aspects of the application of sensors are also included to illustrate how novel sensors may be integrated into the overall life cycle management process. Consequently, discussions of requirements and progress in data fusion and decision support are also included.

Sensors for Diagnostics

For industrial gas turbine applications, certain operational characteristics are notable in recent designs: 100% component (including injectors) accessibility, primary importance for customers is high reliability and availability, optimized compressor and turbine tip clearances, and time between inspection overhauls of 30,000 hours (Teraji et al., 2005). Clearly, the demands on sensors that are part of a life management system are severe.

An appreciation of typical modes of degradation and relevant faults is important in the development of diagnostic systems. The following compilation of experience is provided to guide the identification of needs for sensors:

a) Clogged fuel nozzles (Allison 501-K17: Byington et al., 2002);
b) Inlet guide vane trailing edge damage, increased LP turbine nozzle area, decreased HP turbine nozzle area (J75 engine: Lazalier et al., 1978);
c) Compressor fouling (Allison 501 and LM2500: Byington et al., 2002);
d) Blade health: rubs, cracks and damage leading to imbalance (Hess et al., 2006);
e) Erosion, corrosion, fouling, dirt build-up, foreign object damage, worn seals, excessive tip clearance, burned or warped turbine rotor and stator blades, partially or wholly missing blades, plugged fuel nozzles, rotor disk and blade cracks, inlet air debris including dust and sand (Jaw, 2005);
f) Knife-edge and blade seal wear- seal glazing, seal grooving and seal material transfer to the blade tip. (Hajmrle et al., 2004);
g) Hot streaks at the turbine inlet, combustion instability, emission species variation from individual fuel nozzles, tip clearance in compressors and turbines, losses of blades, vanes, and rub strips (Simon et al., 2004);
h) Oil seal leakage in middle and rear compressor stages and compressor fouling (Rolls /Allison 501-K-17: Scharschan and Caguiat, 2005);
i) Variations in fuel composition and onset of combustion component damage (GE Frame 9: Rea et al., 2003);
j) Thermal barrier coating erosion and delamination (Eldridge et al., 2004); and
k) Oxidation, corrosion, tip shroud curling, platform cracking (Frame –type hot gas path components: Anon b, 2007).

Sensors have long been seen as key elements of condition monitoring and management of gas turbine systems. Best practices have been compiled to document diverse approaches from industry and academia (Saravanamutto, 1990). In addition, simplified methods have been developed to survey radial pressure and temperature distributions with rakes with less expensive manufacture and repair costs (Smout and Cook, 1996). The goal to reduce costs by at least 25%, while retaining performance was achieved with reductions of at least 65% noted.

Specific measurement techniques for industrial engines can be benchmarked with the survey of Valentini et al. (1988). Measurement methods for gas turbine load tests are detailed to emphasize overall and component performance, dynamic response to thermal imbalances, clearances and noise levels. Single point measurements with an infrared pyrometer are described for HP turbine blade temperature. Automated processes were also documented to minimize measurement errors due to velocity, conduction and radiation errors. Relevant work on the development of special diagnostics instrumentation can be traced back to systems specifically designed to reduce overhaul costs (Lazalier et al., 1978). The special sensors used existing access and did not extend into the gas path to minimize possible engine damage. Tradeoffs between component alteration and performance were readily quantified when using the augmented sensor data along with analytical performance models. Expected reductions in performance test failures were sufficient for the system to be introduced into the overhaul process.

Flow area and overall efficiency degradation or damage modes have been diagnosed from gas path methods and conventional pressure and temperatures sensors when combined with aerothermodynamic and data-based models, for example, Lazalier et al. (1978), Sampath et al. (2003), Romessis and Mathioudakis (2005). While these important component-level faults are detectable, certain localized damage is not easily detected. In addition, as condition based maintenance requirements evolve from diagnostic to prognostic functionality, additional data sources should be considered. Byington et al. (2002) also indicate that for advanced prognostics, in the absence of physical models, existing sensors may be insufficient to assess engine condition. Hess et al. (2006) identify the need for a combination of advanced sensors and fault detection techniques to “see” incipient faults as a key element of predicting useful remaining life. For example being able to see sparking and transient blade temperature increases during seal-blade rubs (Hajmrle et al., 2004) could indicate mechanical damage leading to failure and also evidence of increased tip clearances implying reduced efficiency.

Various analytical health management approaches have been identified as hampered by lack of sufficient information and sensors (Jaw, 2005). For example, unique identification of faults and sources on production engines was not generally achievable. While model-based and hybrid methods have been developed with some success, investigation of means to provide additional information to health management processes was judged worthwhile. For this study, the selected sensors needed to be usable in a test cell or production setting and meet the criteria for non-intrusion and ready access for maintenance (Simon et al., 2004).

Sensor research and development for gas turbine applications typically focuses on performance and emissions: current emphasis is on in-situ, non-intrusive measurements in high temperature applications, combustion efficiency, temporal resolution, inferred static temperature, flow velocity and particulate/fuel matter characteristics (Suits et al., 2006). While these broader efforts are monitored, current efforts at NRC-GTL have centred on several sensor technologies with promise for non-intrusive applications in test cells or industrial applications. The prime opportunities identified from our investigations are for "non-intrusive" (readily installed, off engine) sensors that could improve:

a) Detection and quantification of thermal environments likely to cause degradation of engine components and indicative of functional changes in components which may be changed or adjusted, e.g. fuel nozzles; and
b) Detection and identification of particles in the gas stream caused by component conditions associated with decreased efficiency or incipient failure: rubs, combustion process changes, oxidation and corrosion products, and coating loss.

The non-intrusive sensors currently under investigation include infrared thermography, electrostatics, and spectroscopy. The background, progress and plans for these sensors will be described in the next sections.

Infrared Sensor

Mulligan and MacLeod (1998) pioneered work on the application of infrared thermography to engine condition monitoring and fault detection. An IR camera was aimed axially at the tailpipe through a silicon window in the exhaust duct. The baseline images were compared to images from tests with implanted faults. Image subtraction was used to highlight regions where the thermal pattern changed. The images were recorded on SVHS tapes and digitized with a frame grabber before being analyzed using specialized software, one image at a time. Implanted faults observed were fuel nozzle fanning and streaking and combustor can damage. The camera cost was high and the processing technique rather slow and cumbersome, thus limiting broader applications. Other development applications have been documented in recent years. Experimental rig work was done to map the surface temperatures of gas turbine airfoils in a film cooling study (Schulz, 2000). Data on a heated structure in a wind tunnel collected with an IR camera was used to draw shear stress maps (Rudolph et al., 2007); visualization and transient analysis functionality were demonstrated but not in an engine environment.

More relevant applications have been also documented. Isolation of mixer problems with quantitative image analysis tools has been demonstrated on an outdoor gas turbine test stand (Azevedo, 2007). Capabilities for in-house calibrations and bulk processing of images are also described. Thermography has also been successfully applied to inspection of thermal barrier coated gas turbine blades (Marinetti et al., 2007). A high speed IR camera was used with a new data processing technique to find turbine blade disbonding defects in the lab and in situ. Pulsed thermography processes used normally in the manufacturing process had been identified as problematic in service because of irregular optical properties (presence of stains, roughened or eroded areas) accompanying adhesion damage. The field inspections developed involved slow rotation of the component with the engine shutdown with IR imaging at 150 to 1000 Hz. Related work on defect detection has been shown to be effective in high pressure and temperature applications, albeit on pipe segments (Shen et al., 2001). This systematic study was done with wall defects of different depths in different diameter steel and carbon steel pipes.

Infrared sensor progress and plans

NRC is currently running baseline tests with the J85 turbojet engine with two cameras: one tailpipe exhaust axial view and one side view perpendicular to the gas path. Major tasks include development of MATLAB™ software to analyze IR images acquired from a FLIR Indigo Merlin™ camera. For each engine power setting, images are collected and analyzed to obtain average and standard deviation images. Figure 1 shows a sample image from the perpendicular view camera and the result image from the averaging process. For a suspected deviation, the images are compared to the baseline images for deviations from a predetermined norm (Figure 2).

The current system differs from the old system in that images are acquired and processed digitally, rather than digitized from SVHS recordings. More quantitative processing is being implemented along with image alignment processes. The faults likely to be amenable to IR characterization are: combustion can damage and faulty injectors. Ideally as images are collected, the further evolved software will automatically compare new images to the baselines, adjust for ambient condition variation and alignment, and display any inconsistencies.

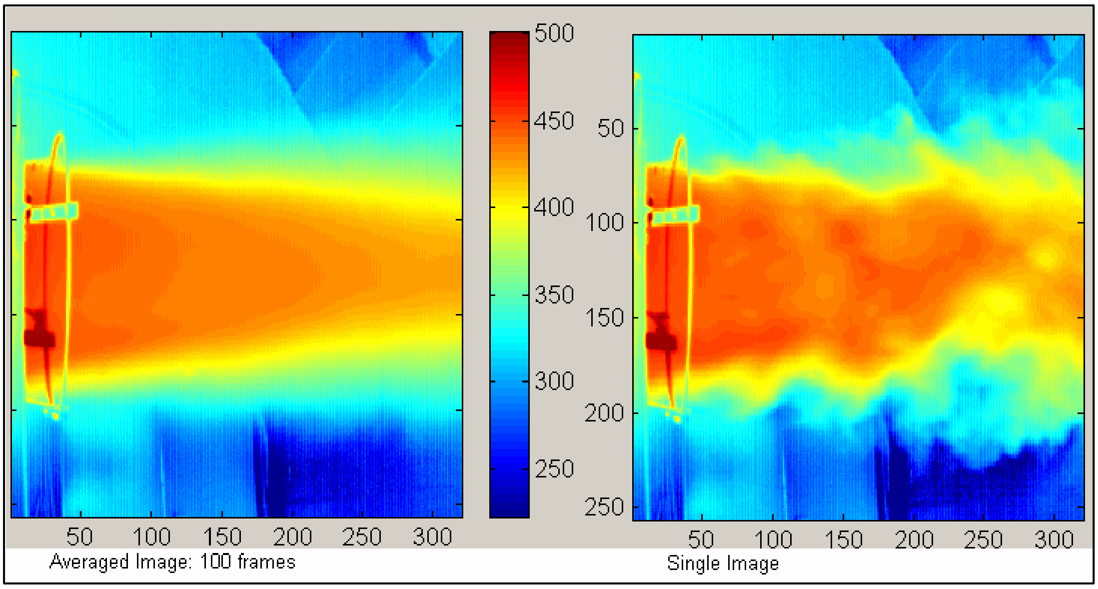

Figure 1: Averaging of infrared images

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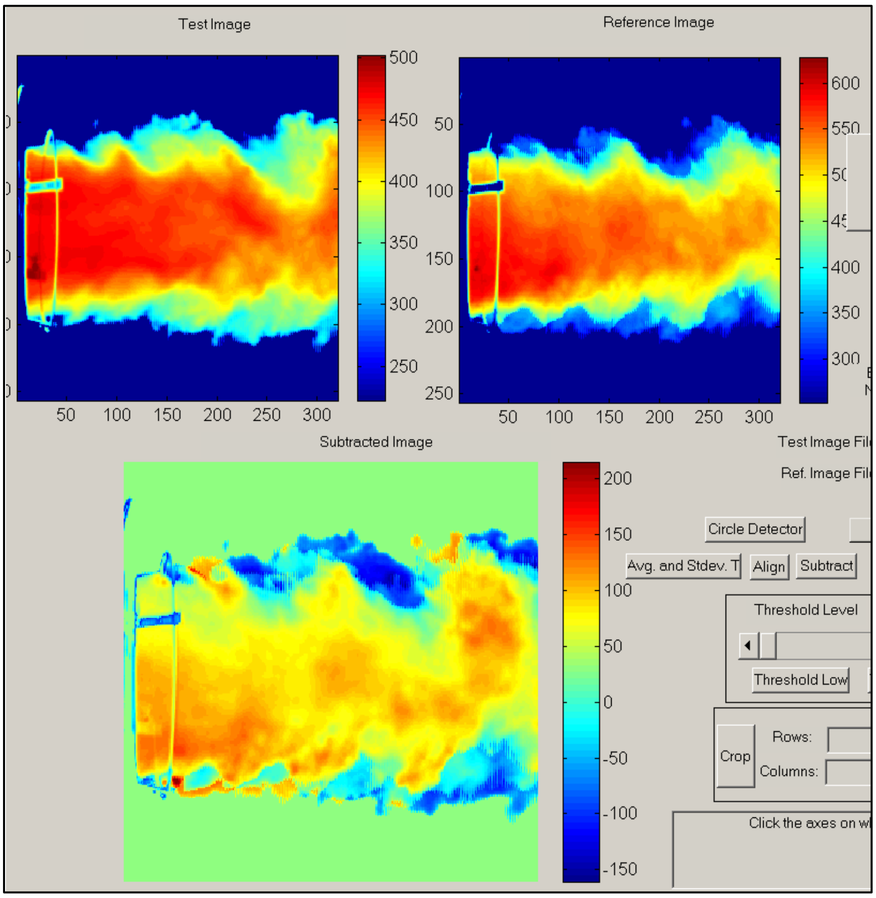

Figure 2: IR image subtraction to identify variations

Electrostatic Sensor

While infrared sensors will provide information on the existence of conditions that could cause engine damage, the detection and identification of actual damage is still a challenge. Electrostatic technology has been used for such condition monitoring. The early work was aimed at detecting engine deterioration during operation through the detection of charged particles in the gas path (Couch, 1978). An Engine Distress Monitoring System was developed to provide quantitative and spatial indications of the internal distress, including blade rubs and combustor deterioration (Powrie and McNicholas, 1997) with application to monitoring the high value demonstrator engine during accelerated mission testing. A broader view of this sensor as a part of a total prognostics system was developed to detect an anomalous situation and to identify the type of fault (Powrie and Fisher, 1999). Time and frequency domain data were used for the application to a ground test series: both EDMS exhaust particles and inlet (IDMS) incoming foreign objects (rocks, sand, metal, etc) were assessed. Several thousand hours of in-flight testing has been completed.

Further integration of the two sensors into a sensor suite with data fusion has been applied to case studies (Fisher, 2001). The broad acceptance of this technology is identified by Jaw (2005), in particular its acceptance for installation on the production version of the Joint Strike Fighter engine. The Society of Automotive Engineers has also developed and maintains an information report on the technology: SAE AIR 4986 Engine Electrostatic Gas Path Monitoring.

Electrostatic sensor progress and plans

NRC has conducted validation tests with the Stewart Hughes EDMS on turboshaft engines in a test cell environment. Metal particles injected in the compressor and turbine were detected in the engine exhaust during operation in a test cell.

Modifications have been made to improve the sensor to give more consistent and reliable results. Baseline tests are currently being done on a J85 turbojet engine in a test cell. A hoop sensor is located at the rear of the engine around the tail pipe. For each engine power setting, recordings are being made for later comparison. Any deviation from the baseline runs will be correlated with the implanted faults. For this sensor, turbine rubs and combustor soot are to be introduced. If reliable data can be collected and proven to show problems or faults in operating engines, sensors will be installed in all NRC test cells. Studies to implement data fusion algorithms with vibration and acoustic data are anticipated.

Spectroscopy

While the combination of infrared sensor and electrostatic sensor will identify the conditions for damage and the presence of particles, the identification of the source of the damage is a challenge. Spectroscopy offers the means to identify the elemental composition of the particles in the gas path.

Typically spectroscopy has been used to identify gaseous elements in exhaust flows as part of emissions sampling, e.g. water, carbon and nitrogen compounds (Marran et al., 2000 and Shafer et al., 2005). With higher temperatures and energy levels, rocket applications have been successful in detecting trace quantities of metal particles, e.g. iron, chromium and nickel, as a means of condition monitoring for turbo pumps and other fuel system components (Rai et al., 2003).

The specific method of laser induced breakdown spectroscopy (LIBS) has been used in a number of applications relevant to gas turbine operations. Particulate detection was demonstrated in the exhaust nozzle of a turbine (Baldwin, 2006): magnesium was detected in the exhaust nozzle of a turbine when seeded magnesium chloride was introduced upstream. The system was also able to detect carbon, nitrogen and oxygen in the exhaust stream during normal operation. Further development of this spectroscopy method has sought to determine systematically the effect of varying temperature and aerosol dispersion on mass detection limits for chromium, magnesium, titanium and manganese (Kratzsch, 2004). Sampling was done on a rig designed to simulate a gas turbine-like environment.

Spectroscopy progress and plans

Earlier work had sampled engine exhaust following an induced turbine rub to successfully detect nickel through off-line processing. Figure 3 shows that the rub event at 95% power generates a significantly different amount of nickel after the turbine compared to a reference level in the stream at the compressor exit. The rub event is clearly isolated during the 10+ minute test period.

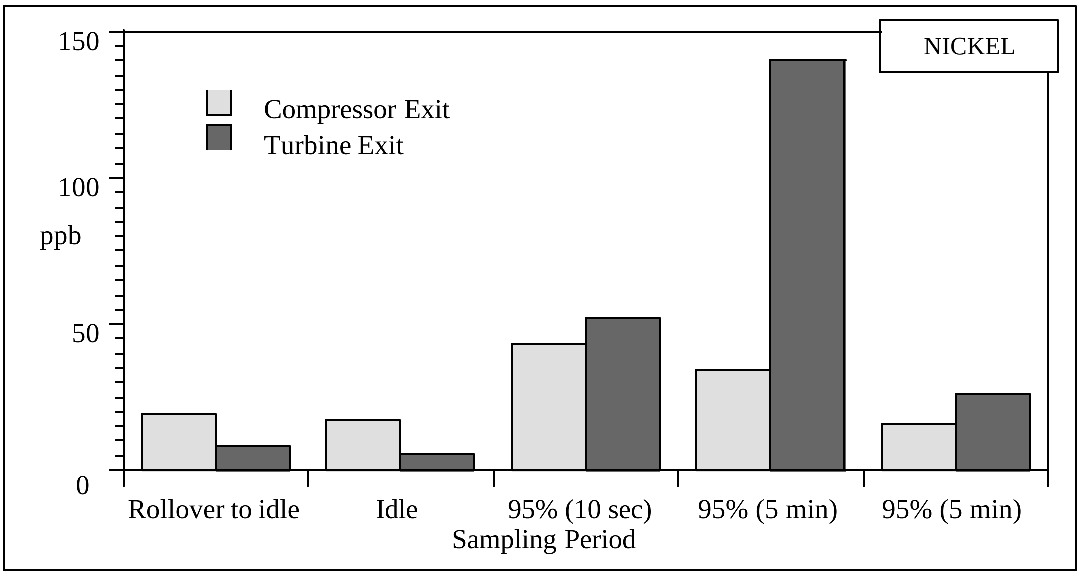

Figure 3: Detection of nickel during turbine rub events

An on-line LIBS system is currently being commissioned for gas turbine applications. Bench tests with different metal powders have been promising. Figure 4 shows the results for a multiple injection of titanium powder. The software identifies the detected wavelengths and the possible elements corresponding to these lines. Particles from rubs, combustion carbon and gases, coatings and foreign objects will be simulated. Bench tests of particles in airflow streams are being set-up prior to tests on a J85 turbojet engine in an NRC test cell.

Efforts will also concentrate on the development of practical spectroscopy systems for use in test cell and field installations. The practicality of optical sensors in service is evolving. Umezawa (2005) describes the development and fielding of a laser based torque-sensing system in commercial electrical plants for stream and gas turbine torque measurement. Applications to detecting the degradation and loss of metallic and also ceramic thermal barrier coatings should be of interest.

Bench testing is currently under way to establish a practical methodology and setup to implement into test cells or other facilities. The testing will verify that the laser-induced breakdown spectroscopy (LIBS) method can identify the wide variety of engine materials in relevant concentrations under the range of conditions to which a gas turbine is exposed during its lifetime. The goal is to have accurate real-time data to warn engine or facility operators of a problem developing, the source and preferably the severity, e.g. to show engine degradation that occurs over various timeframes.

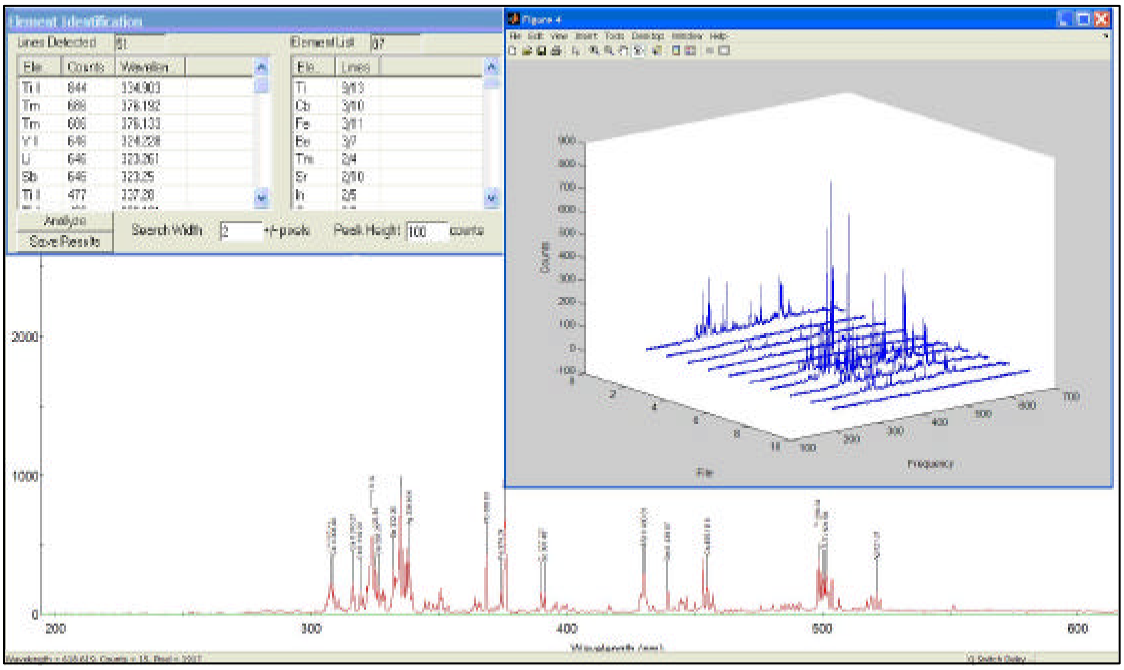

Figure 4: Spectroscopy identification of several titanium powder samples

Data Fusion

Effective engine health management is seen to require monitoring results from more than one functional area (gas path, performance, vibration, oil) through information fusion to make the most educated decision (Jaw, 2005). Even surveying hybrid and model-based methods, Jaw concluded that unique identification of faults could not be generally achieved because of lack of information due in part to insufficient numbers of sensors. An overview of the integration of data and analysis that enables decision-making and life management is provided by Hess et al. (2006). The implied use of various data driven algorithms requires that data of various types and sources be merged or fused to provide the best possible information: applicability across usage and ambient conditions, and robustness to noise and sensor failures are highlighted. While the viability of vibration methods for PHM contributions is acknowledged, the need is identified for more effort on the part of designers to integrate vibration analysis with other PHM technologies.

Of particular interest in implementing sensor suites is the detection of sensor faults and isolation from the component faults. Analytical methods have been proven to be effective in the detection of faults including estimation of the magnitudes of the biases even in the presence of component degradation (Romessis and Mathioudakis, 2005). However, the probabilistic approaches often employed benefit from the diversity of data available; other sensors inputs should be beneficial and the methods reported may be adapted to guide the selection and application process.

The integration of sensors into diagnostic systems is being accomplished through the use of existing Failure Modes and Effects Analysis tools (Logan, 2002). Known or expected failure modes and consequences are thus included in the assessments of sensor needs and performance metrics. In addition, the growing use of advanced duplex systems to improve availability in industrial machines (Schulke, 2004) provides a direct application of data fusion methods through redundancy and validation functionalities from diverse sensors. The expandable signal acquisition and processing capabilities should provide the means for ready integration of new proven sensor technology. New methods of data fusion are being developed which capitalize on data streams from nominally healthy systems, i.e. without implanted fault data, and identify sensor faults (Xu et al., 2006). Specifically aimed at nonlinear systems, fault isolation and fault size estimation functionalities are possible for both sensor bias and drift. The method could also be applied to estimate the required accuracy for diagnostic effectiveness and also to select suitable sensor suites.

The maturation of data fusion methods provides an important base for the development work in sensors to contribute more directly to gas turbine life cycle management: integrate new and existing sensor information, evaluate the marginal contributions of new or existing sensors to diagnostics and buttress these with quantitative confidence data.

Progress on data fusion

Two key aspects of data fusion are the integration of diverse data sources and visualization of the data for analysts. The data fusion experiments being conducted at NRC are being supported by the development of a data analysis software environment to meet these two requirements.

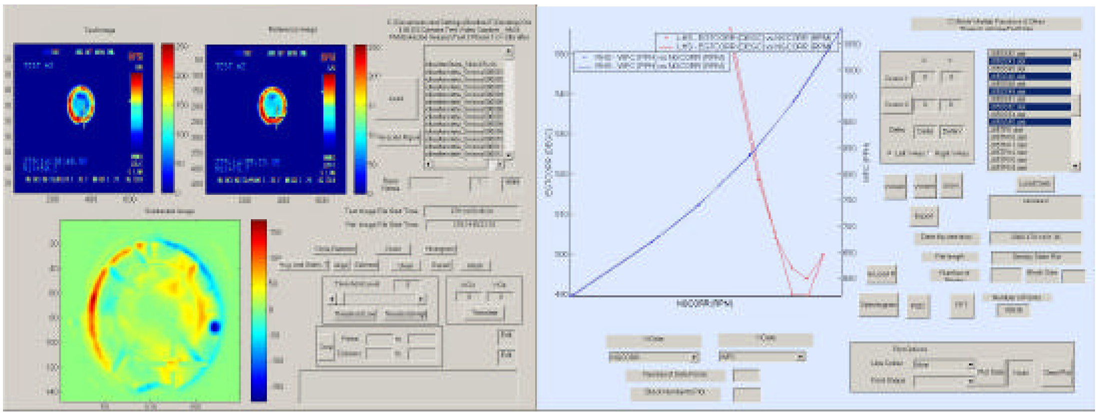

Figure 5: Data Fusion Analysis Environment for infrared and performance data

Figure 5 shows prototype screens of the system under development that allows an analyst to visualize and conduct qualitative and quantitative studies of multiple sensor data. Exhaust infrared image presentation and analysis (left frame) is coupled with exhaust gas temperature performance presentation and analysis (right frame). Both pre-selected and investigative presentations are possible with the developer concentrating on quantitative results and synthesis of information and not data manipulation.

Decision Support

Sensor development processes should be viewed as the basis for reliable decision support systems for use by operators. This end use provides the requirements for sensor development and sensor research should offer new opportunities to improve or extend information and confidence for operators. Hess et al. (2006) indicate that the arrival of advanced life prediction systems will include the automatic monitoring of measurable wear and engine degradation characteristics to support prognosis of impending maintenance actions. Confidence in these PHM system recommendations will require quantification of actual fleet trends and field experience. This can be accomplished by robust and pervasive sensor suites to feed statistically relevant data on degradation and failure modes, particularly over the extended lives of current systems. Processing and operator interfaces aimed at increased confidence in component and systems health and increased warning of impending combustor liner failures are being developed and integrated into the field (Rea et al., 2003). Other decision support information is provided as combustor-to-combustor imbalances through such evolving on-line systems.

Two important functions of a decision support system for operators would be the association of symptoms to faults and the ability to accommodate changes of operating conditions. The information from sensors and associated confidence levels are key contributors to these functions. The next two sections offer an example of how such functions may be provided.

Associate symptoms to faults

Bourassa and Bird (1996) adapted a neural network method to characterize the differences in fault signatures. Typically a maintainer would need to review many plots to ascertain the likely fault condition of an engine. The approach produces a visualization of the engine state in one plot of the current condition of the engine relative to the selected faults, with an indication of the severity of any fault conditions.

Figure 6 shows the results of a characterization of component-level faults for a T56 engine at a high power operating point. Any new operating point of the engine would be a point in the 3D plot. The centre circle is the region of healthy engines while outward vectors correspond to faults- the more severe the condition, the further away from center. It can be seen that the typical component level faults show unique characteristics in this presentation.

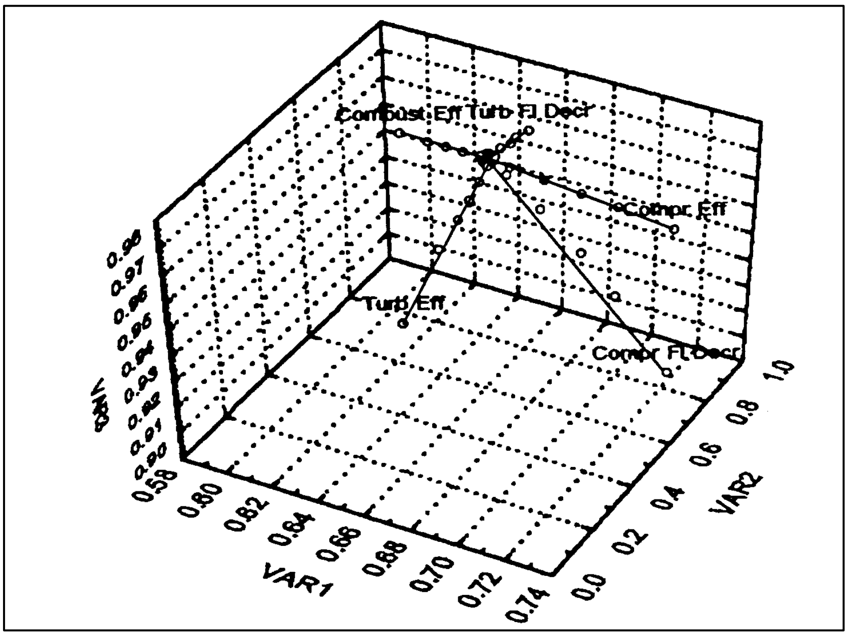

Figure 6: Engine fault plot

Applications for real operations

From anecdotal evidence, it is sometimes observed that it is more difficult to diagnose faults depending on ambient conditions. Bourassa and Bird (1996) extended the method of the previous section to examine the changes in fault characteristics for cold days compared to hot days. Figure 7 shows that the distance from the healthy centre point in Figure 6 is significantly different for these two ambient conditions.

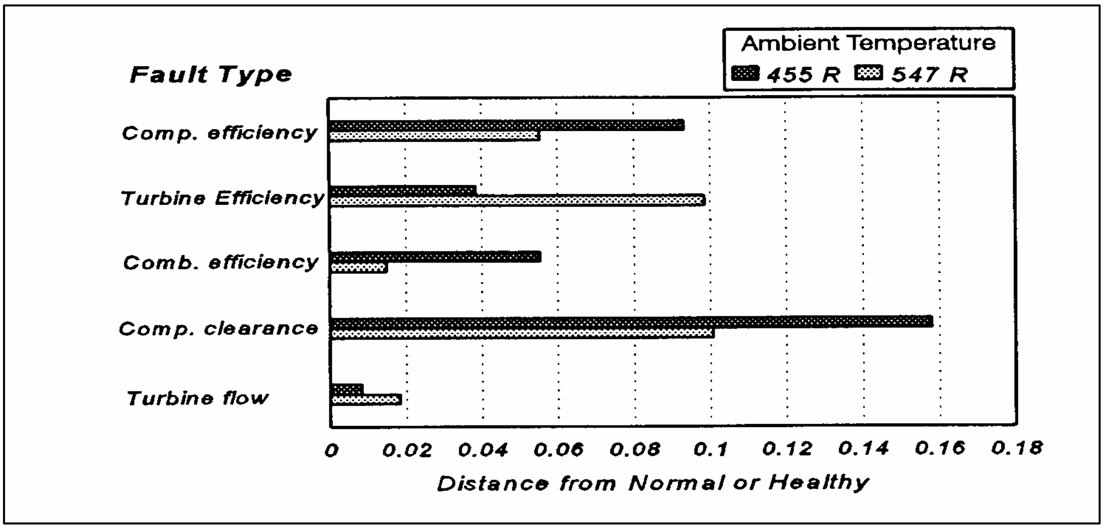

Figure 7: Differences in fault characteristics on hot and cold days

It can be seen that turbine efficiency faults will be much easier to isolate on hot days and compressor clearance faults will be more distinct on cold days. Further work is planned to improve the ability of decision makers to discern engine faults in an easy to visualize way.

A more conventional neural network approach has also been recently demonstrated on model data for a Siemens V94.3 (Bettocchi at al., 2006). The robustness of the component level fault isolation to sensor biases and noise was demonstrated over a range of operating conditions. However, the models robustness was reduced with limited or reduced sensor suites in the gas path.

Conclusions and Opportunities

This report has identified a number of sensors and related analysis methods, which should offer advantages to operators of industrial engines. Additional information is possible on engine performance and especially component condition with limited impact on the engine-specific installation. That is, sensors can be added to the facility in way more or less non-intrusive to the engine. The ultimate goal is to produce a "suite" of equipment utilizing infrared, spectroscopy, electrostatic and possibly acoustic sensors in one practical package. As part of an engine health management system, the sensor suite could be then used for early detection of problems, possibly avoiding unnecessary inspections and teardowns.

The ability to develop and field such non-intrusive sensor technology is seen to hinge on access to physical and organizational resources. Some opportunities are identified.

Technology demonstration

Test opportunities on engines or rigs are on going at NRC to spur development of practical sensor technology. A J85 turbojet engine, and T400 and T56 turboshafts are being used at the Gas Turbine Lab to gather sensor suite data with implanted faults in a test cell setting. Additional opportunities are sought to define test plans, and add prototype sensors to existing installations to compile operating experience and build confidence in the technology.

Partnerships

Government-industry fora like the IAGT are seen as important opportunities to define needs and showcase appropriate technology. Several other like opportunities are described in this section. The authors can provide contacts within the initiatives.

DPHM Working Group

The industry-led, government-supported initiative aims to identify and facilitate projects to advance prognostics and health management technologies in Canada. A number of operator-oriented projects are underway or in the process of definition. Full details can be found on the website: www.dphm-canada.org.

EHM Industry Review

Jaw (2005) provides the rationale for an initiative by the health management community to significantly advance the rate and effectiveness of developing fieldable systems. Jaw proposes an industry and community review to define a set of theme problems, invite experts in industry and academia to solve these problems and conclude by a conference to present the results, share experience and identify gaps. The theme problems will initially comprise gas path performance and vibration analysis domains but oil and debris monitoring and usage and life monitoring themes have also been proposed. International cooperation and participation is being fostered through the auspices and agreements of The Technical Cooperation Program. In Canada, the Gas Turbine Laboratory is the current point of contact.

Others

As evidence of integrated planning of health monitoring capabilities, the Structural Health Monitoring – Aerospace Industry Steering Committee includes industry, regulatory agencies, government agencies and research and development institutions (Anon, 2007). The aim is to formulate a collective approach to implement technology through the development of standards, procedures, processes and guidelines for implementation and certification.

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Biographies

Jeff Bird *is a Senior Research Officer in the Gas Turbine Laboratory of NRC. He is a member of technical committees under ASME Controls, Diagnostics and Instrumentation, SAE E32 and The Technical Cooperation Program. His current research interests are engine performance assessment, signal processing, health management applications and non-intrusive diagnostics.*

Brian Galeote *is a technical officer in the Gas Turbine Laboratory at NRC. His current research interests are health management applications, non-intrusive diagnostic, signal processing, ice crystal technology and spectroscopy. He has a background in IR, high-speed data acquisition, vibration, flight impact simulators, foil bearings and high-speed bearings.*

Tim Breithaupt *is a technical officer in the Gas Turbine Lab at NRC. He has been performing data acquisition and analysis with vibration, IR and other assorted non-intrusive diagnostic systems. He works with the instrumentation group and is also responsible for high speed, infrared and standard video and lighting for the lab.*