Paper No: 09-IAGT-304

INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

Progress on Some Non-Intrusive Monitoring Technologies for Gas Turbine Operators

by

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Presented at the 18th Symposium on Industrial Application of Gas Turbines (IAGT)
Banff, Alberta, Canada – October 2009

Abstract

New and evolving sensor technologies have the potential to improve diagnostics for high value gas turbine machinery. In addition, development and maintenance test cells and other ground–based installations are seen as important technology demonstration targets for applications to benefit operators. Practical applications are sought in the work reported employing non-intrusive sensors that can be installed readily as part of working gas turbine installations. Current capabilities and results from baseline and fault implanted engine tests are discussed for infrared, audio and electrostatic sensors. Evolving work on spectroscopic methods is also shown because of the significant benefit of identifying specific components and failure or degradation modes. Opportunities for the user and technology communities are discussed as part of the planned work.

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Background

The National Research Council Canada has maintained involvement 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. The range of applications has been from development to certification so improvements are motivated by safety and cost effectiveness: usually the high value test engines and/or the extensive instrumentation are unique and may be prototypes or experimental in nature.

While most laboratory and client-driven 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 with emphasis on calibration and practical applications. The Institute for Information Technology has been instrumental in introducing and applying appropriate expert systems, data mining and other analysis techniques. Specialists in the Institute for Aerospace Research have contributed planning, experimentation and analysis skills in combustion, performance correlation, environmental simulation, novel materials, non-destructive inspection, droplet sampling, inlet aerodynamics, and noise. The result is that specialized methods and equipment, available in a laboratory setting have been assessed and often adapted for use in a test cell environment.

Users with operations and maintenance (O&M) issues typically have limited instrumentation and capability to address their complete needs: assess engine condition, confirm an anomaly and isolate to a component. Operational procedures and equipment have usually been designed for limited performance measurements, robust operations, rapid turnaround and minimum cost rather than adaptability. In addition, the complexity and cost of current propulsion and power systems limit the test opportunities to gather additional information to support operations and maintenance decisions.

Such system health management is also a focus of new developments in gas turbines. The associated advanced technology programs like the Joint Strike Fighter and distributed control offer operators of legacy engines access to potentially useful technology developments.

The Department of National Defence, Defense Research and Development Canada (DND-DRDC) and NRC work cooperatively on integrated engine health management technology. The objective of this work is to develop and demonstrate integration processes for performance modeling, data management, sensors and life estimation that will advance the capability for cost effective and safe life cycle management of the Canadian Forces' engine fleets. Details on the multidisciplinary advances may be found in Wu et al. (2007).

The current development work at NRC, under this partnership, is aimed at improving the application of sensing technology to real life engine performance/condition assessment during operations. Specifically, the work is to provide test operators and analysts with unique or value-added information on engine and component condition and safety. The intent is to increase the value of costly test time by supplementing conventional sensor suites employing pressure, temperature and vibration. A particular focus is on non-intrusive sensors, which can be located externally or remotely from the engine or component under test. This approach is to allow ready application to high value engine assets without the overhead of extensive certification, complex wiring and internal installation. This emphasis should also allow the transition of promising applications to a production or overhaul test cell, ground installation or possibly to the flight line.

Approach

Our approach is driven by an awareness of these operator issues similar to our own need to maximize test output. These needs coupled with access to diverse laboratory grade sensors, has identified a number of promising opportunities. 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.

Emphasis of this work is on the development of sensors that contribute to life cycle management of gas turbine systems. In general, the work continues to be primarily experimental in nature with sensors assessed and demonstrated on test benches and in the test cells. The work centers on a technology demonstrator platform- a modified CF-700 engine that provides an environment for sensor development and evaluation. With reference to a previous IAGT paper (Bird et al., 2007), NRC continues to concentrate on a diverse sensor suite, which is considered applicable to legacy propulsion systems like the T56 or 501.

Sensors for Diagnostics

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. While these broader efforts are monitored, current efforts have centered on several sensor technologies with promise for non-intrusive applications in test cells or industrial applications. The prime opportunities identified from our investigations (Bird et al., 2007) are for sensors that could improve:

a) Detection and quantification of thermal environments likely to cause degradation of engine components and/or indicative of functional changes in components which may be replaced in service 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, e.g. rubs, combustion process changes, oxidation and corrosion products, and coating loss.

The non-intrusive sensors currently under investigation are based on principles from infrared thermography, audio, electrostatics, and spectroscopy. The current efforts are centered on documenting and correlating the variations in sensor data over the operating range of an engine. This baseline provides a reference for the second part which is the detection and correlation of the effects of implanted faults of relevance to operators:

a) restricted flow fuel nozzle as would occur with fouling
b) turbine rub associated with power and temperature transients

Presentation of these results is followed by a discussion of future work priorities.

Infrared Sensor

It has already been established that an infrared (IR) camera can be used to detect problems with the combustor and fuel nozzles. However, with advances in its respective technologies, we can now see images in much greater detail and processing time has been greatly reduced. We are now capable of seeing problems that arise in a real-time environment.

Two infrared cameras were used. One was dedicated to an axial view, located in the exhaust duct, looking into the turbine section of the engine. The other camera was used in several locations, viewing different areas of the engine under various conditions.

The primary camera used for the axial view was the Merlin™. It is a mid-wavelength infrared (MWIR) high-performance camera made by Indigo Systems Corp. It consists of a Stirling-cooled Indium Antimonide (InSb) Focal Plane Array (FPA) built on an Indigo Systems ISC9705 Readout Integrated Circuit (ROIC). The FPA is a 320 x 256 matrix that is sensitive in the 1-3 to 5-5.4 _m range. The FPA is enclosed in an all-metal evacuated dewar assembly cooled by a closed-cycle Stirling cryocooler, and is thermally stabilized at a temperature of 77 K. A real-time, 60 Hz, 12 bit digital data stream is one of the standard output formats. The camera operates the InSb FPA in a single output, full frame, 6 Mpixel/sec mode. The full 320 x 256 FPA operates at a frame rate of 60 Hz in an NTSC camera configuration. The analog video frame rates are 30 Hz for NTSC. It has a calibrated temperature range to 2000°C.

The camera used for the other views was a ThermoVision A320. It is a long-wave camera with an uncooled microbolometer FPA. It has a spectral range of 7.5 to 13 _m with a matrix of 320 x 240. Temperature ranges can be setup from 21°C to 1200°C with a detectable temperature variation as small as 0.08°C. Ethernet image streaming is 16-bit 320 X 240 pixels. An NTSC 30 Hz signal can also be used through the c-video connection.

Infrared sensor baseline results

Baseline tests were run with the turbojet engine using the two cameras: one tailpipe exhaust axial view and one side view perpendicular to the gas path. Contributing efforts included development of software to analyze IR images acquired from the cameras. For each engine power setting, data were collected and analyzed to obtain average and standard deviation data. Figure 1a shows a sample image from the perpendicular view camera and the result image from the averaging process. A standard deviation plot provides a simple indication of the variability in the jet which could be related to changes in engine operation/condition or emitted noise. For a suspected fault or repeatability issue, the images can be compared to a reference data. Variations from a predetermined norm are readily quantified in a difference image (Figure 1b).

The images are acquired and processed digitally with the current system. More quantitative processing is being implemented along with image alignment processes. Ideally as images are collected, the enhanced software will automatically compare new images to the baselines, adjust for ambient condition variation and alignment, and display inconsistencies.

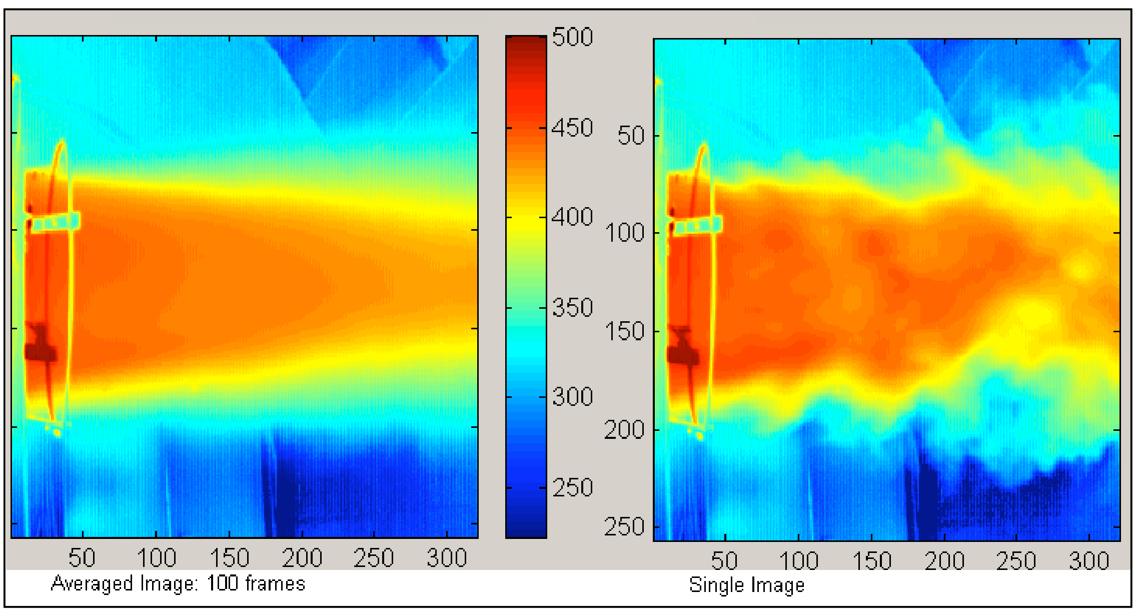

Figure 1a: Averaging of infrared images (with temperature scale in degrees C)

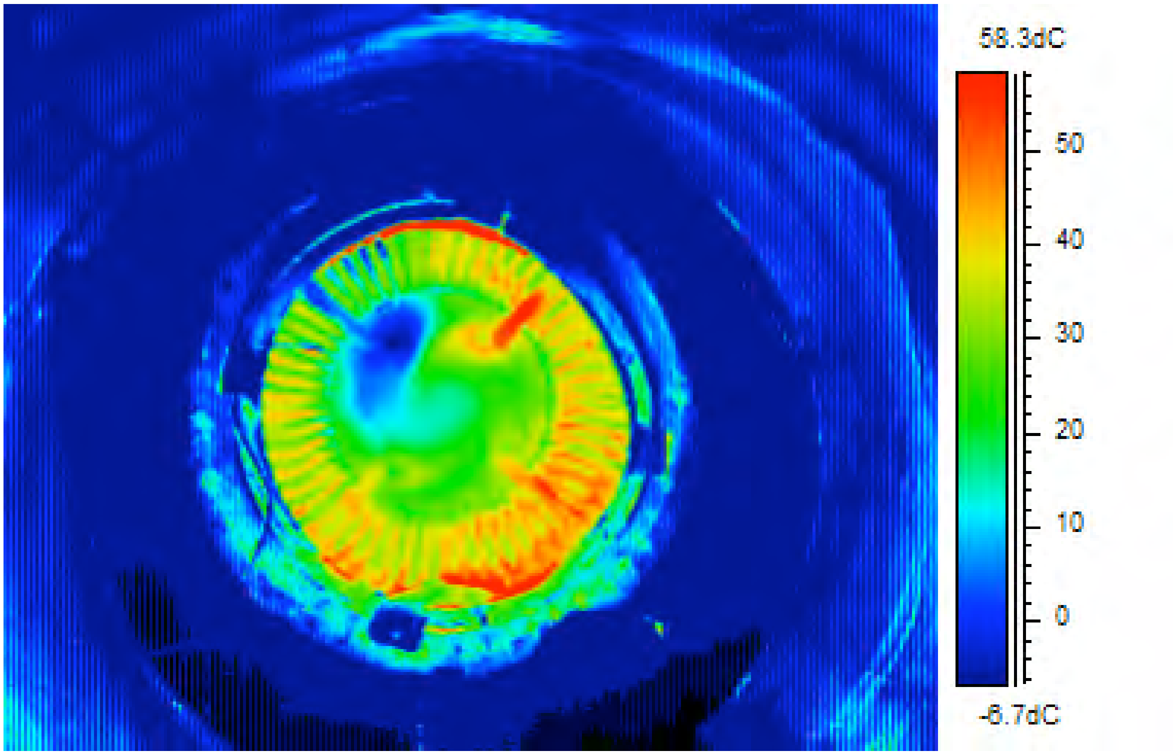

Figure 1b: IR image subtraction to identify variations

In quantifying the IR characteristics of the baseline or healthy engine, the variation with power setting is important. Figure 2 to 5 show comparable images at idle (50%), 65% power, 80% and 85% rotor rotational speed. The low power settings (and the engine's relatively high idle exhaust gas temperature) result in changes in the absolute level of the measured exhaust gas temperature of 51° C. This similarity and the consistency of the thermal patterns are evident in the figures. The tests also documented an even circumferential heat distribution in the turbine.

When comparing the image-derived EGT to the engine thermocouple set, there is only a 2°C difference.

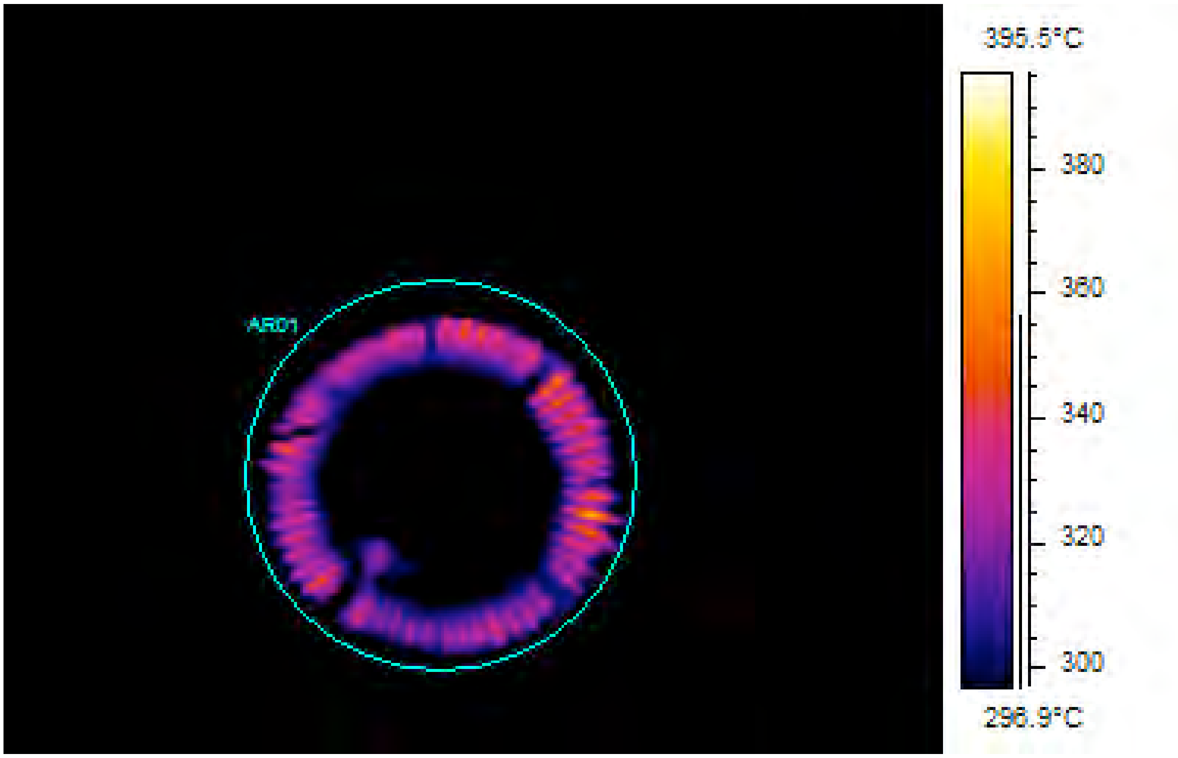

Figure 2: IR image of NRC engine turbine during a baseline run at Idle (50%)

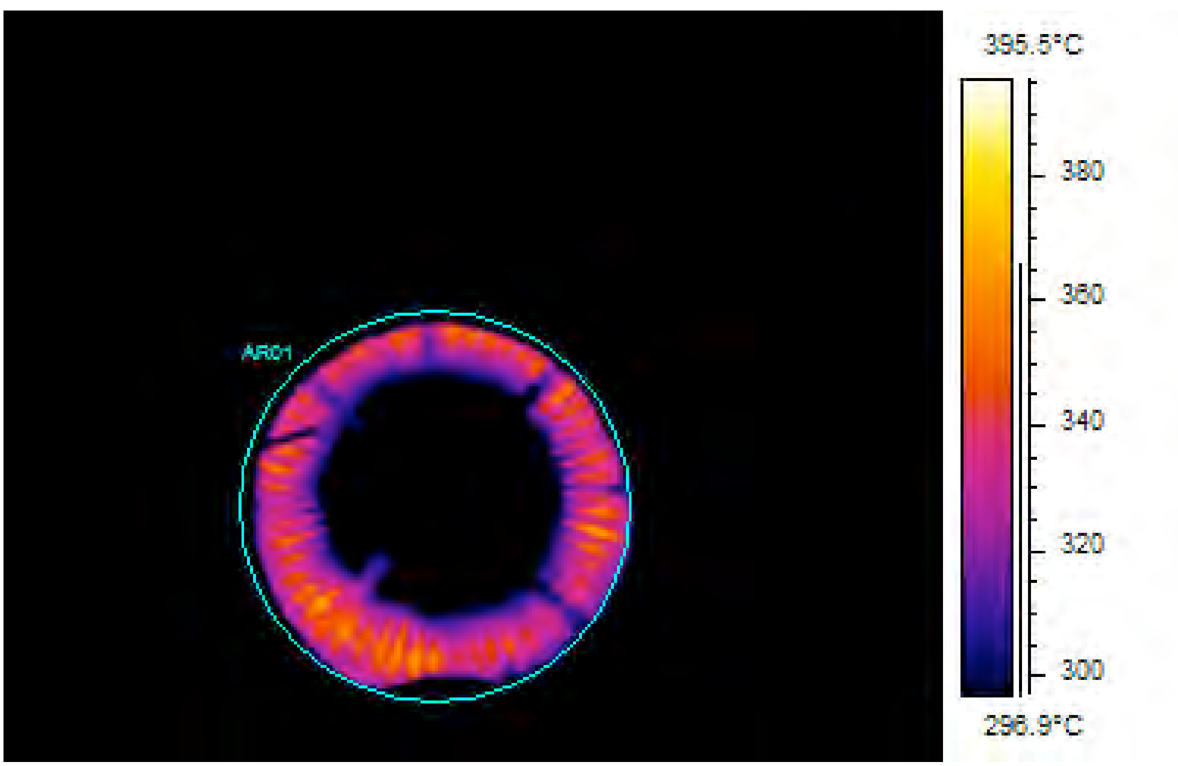

Figure 3: IR image of NRC engine turbine during a baseline run at 65%

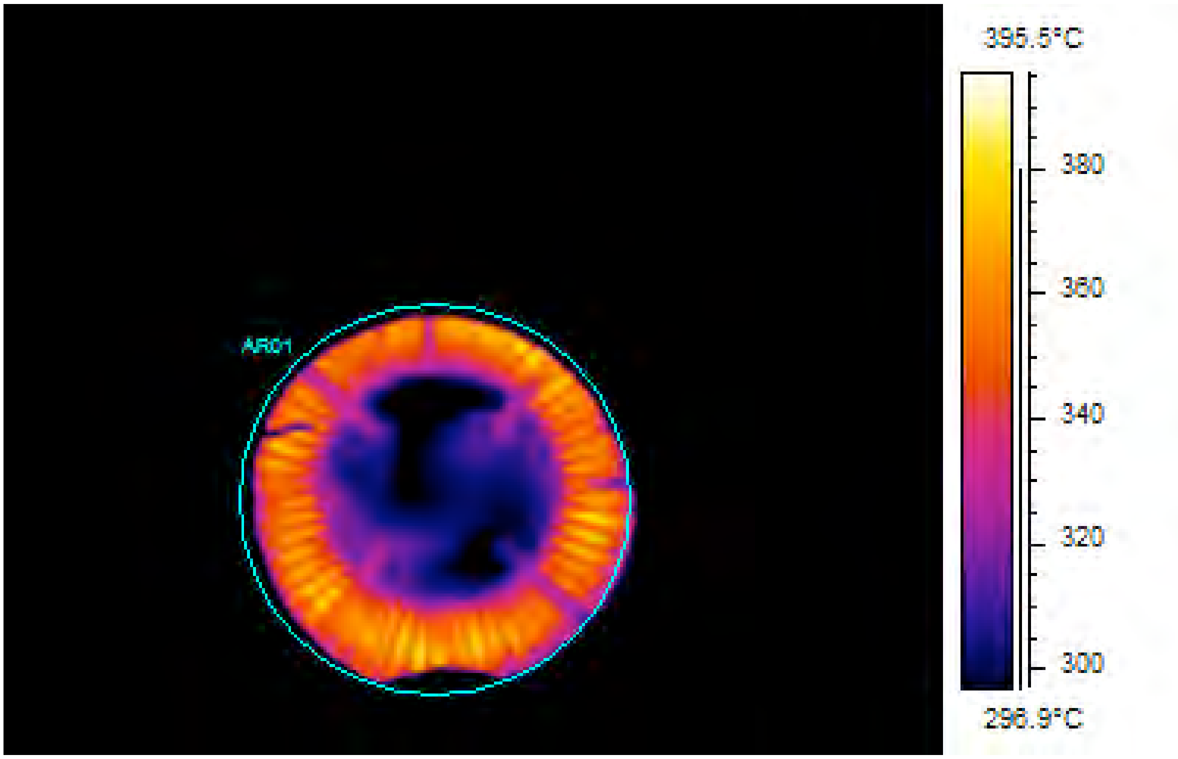

Figure 4: IR image of NRC engine turbine during a baseline run at 80%

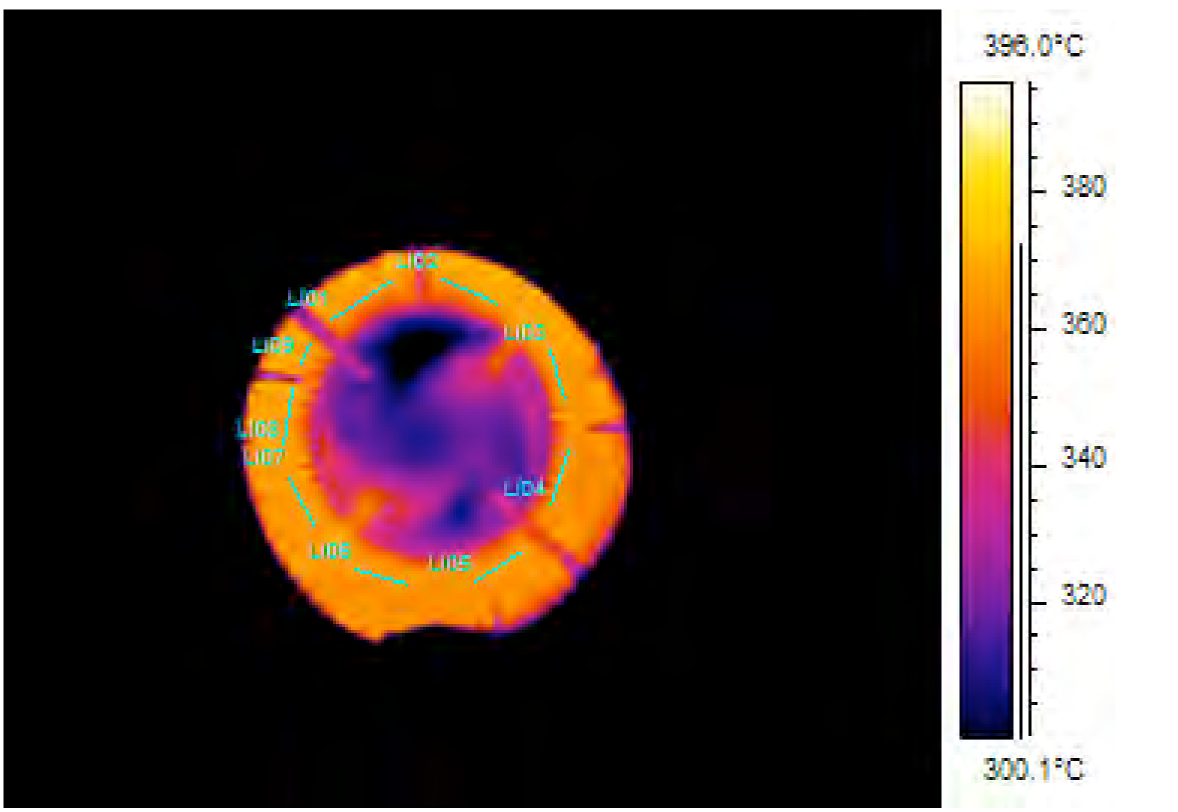

Figure 5: IR image of NRC engine turbine during a baseline run at 85%

Infrared sensor fault implementation results

This fault implementation was done by restricting the flow to one of the twelve fuel nozzles. Figure 6 shows an obvious difference between baseline conditions (Figure 5) and the faulty nozzle experiment. The flow in the region of the faulty nozzle (top left corner-location labeled L101), was 14°C cooler while the other nozzles had an increase of 21°C, as determined by use of the camera software. The IR image shows this reduction in the location of the closed nozzle. In fact, even minor changes to the nozzle assembly were detected by the infrared camera. The increase in temperature at locations L102 to L109 was necessary to keep engine speed at 85%, compensating for the reduced temperature in location L101. At higher speeds with engine temperature limits, solely relying on averaged EGT measurements could mask localized problems in the combustion chamber.

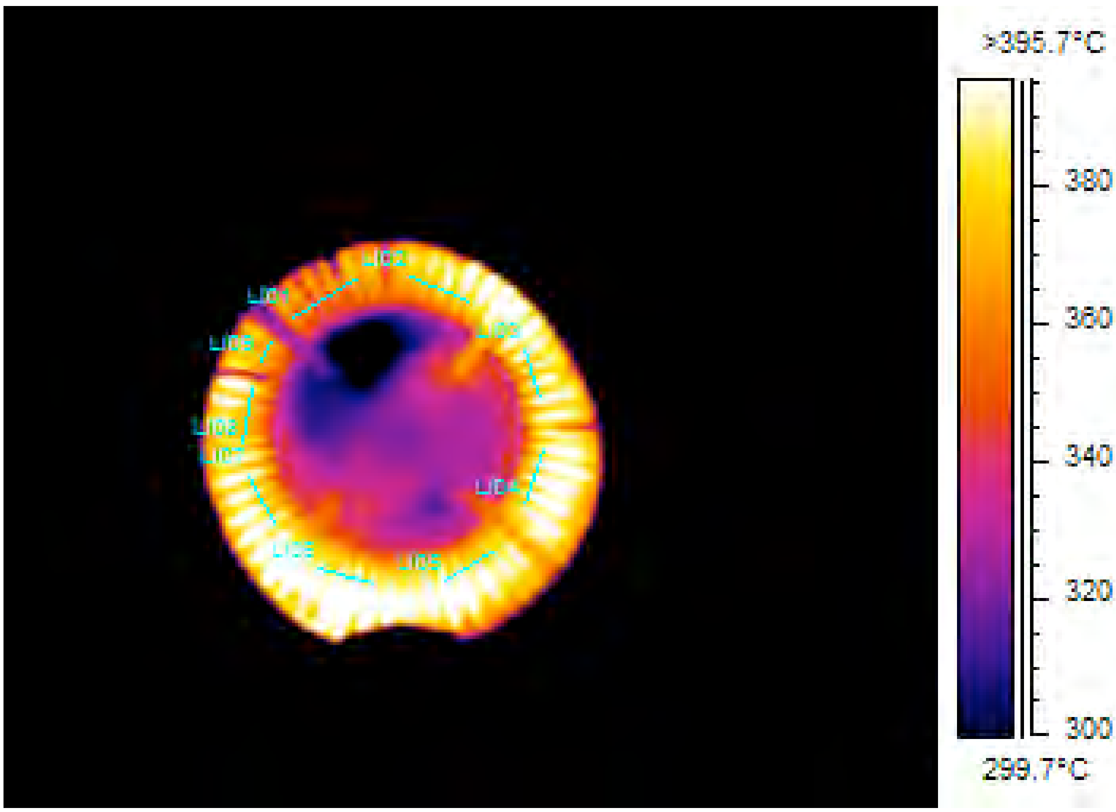

Figure 6: IR image of NRC engine turbine with a faulty fuel nozzle at 85%

The second fault type was a seal rub. This was caused by installing the casing seals with below specification clearances. There was no evidence of the seal fault when observed with the IR camera but further tests and processing are being investigated.

Another operational mode useful for fault detection is the start sequence. This process may be affected by fuel control or facility faults, e.g. air or fuel supply with significant over-temperatures and possible damage. IR image sequences during startup show individual light up of the fuel nozzles when the igniters are turned on and fuel is added.

Figures 7 a to e show the sequence in the initial second of the engine start. The reduced temperature in the top left-hand corner of the turbine corresponds to the location of the nozzle that was completely closed. With no fuel flow to that area of the turbine, consequently no ignition, there's a considerable temperature drop in that area.

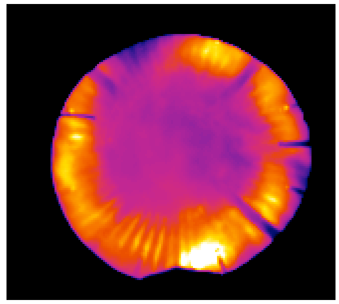

Figure 7a: IR image of NRC engine turbine during startup- first image

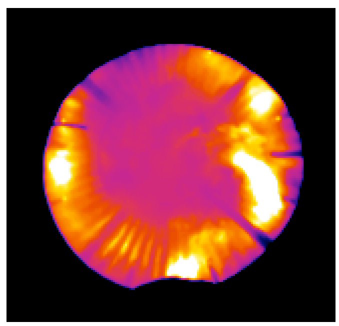

Figure 7b: IR image of NRC engine turbine during startup- second image

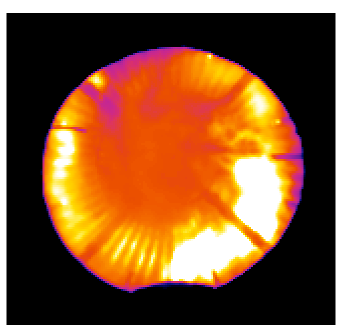

Figure 7c: IR image of NRC engine turbine during startup- third image

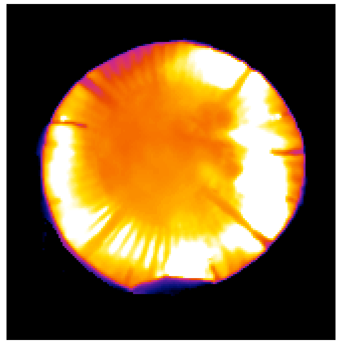

Figure 7d: IR image of NRC engine turbine during startup- fourth image

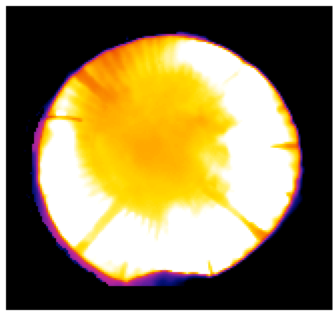

Figure 7e: IR image of NRC engine turbine during startup- fifth image

Audio Sensor

While acoustic indications of changes in engine operation are often part of practical trouble-shooting, quantitative methods are not widely available. Microphones of type 4939 Bruel & Kjaer (B&K) were calibrated using a 4231 B&K sound calibrator. They were installed in the plane of the engine inlet (front) and engine exhaust (back) and recordings were made at a sampling rate of 50 kHz with a 20 to 100 kHz filter.

Audio sensor baseline results

The variations in acoustic spectra with different power settings are shown in the Figure 8 (three rotor speeds). It is seen that the spectra exhibit features of several compressor stages (based on blade counts) and their corresponding harmonics. For example in Figure 8a, the peaks are found at the following frequencies:

a) stage 1: 4140, 8289
b) stage 2: 8020, 16040
c) stage 3: 11629

Another significant energy peak is evident at 10022 Hz, which likely corresponds to the 1^{st} stage turbine based on the rotor speed and unique number of blades.

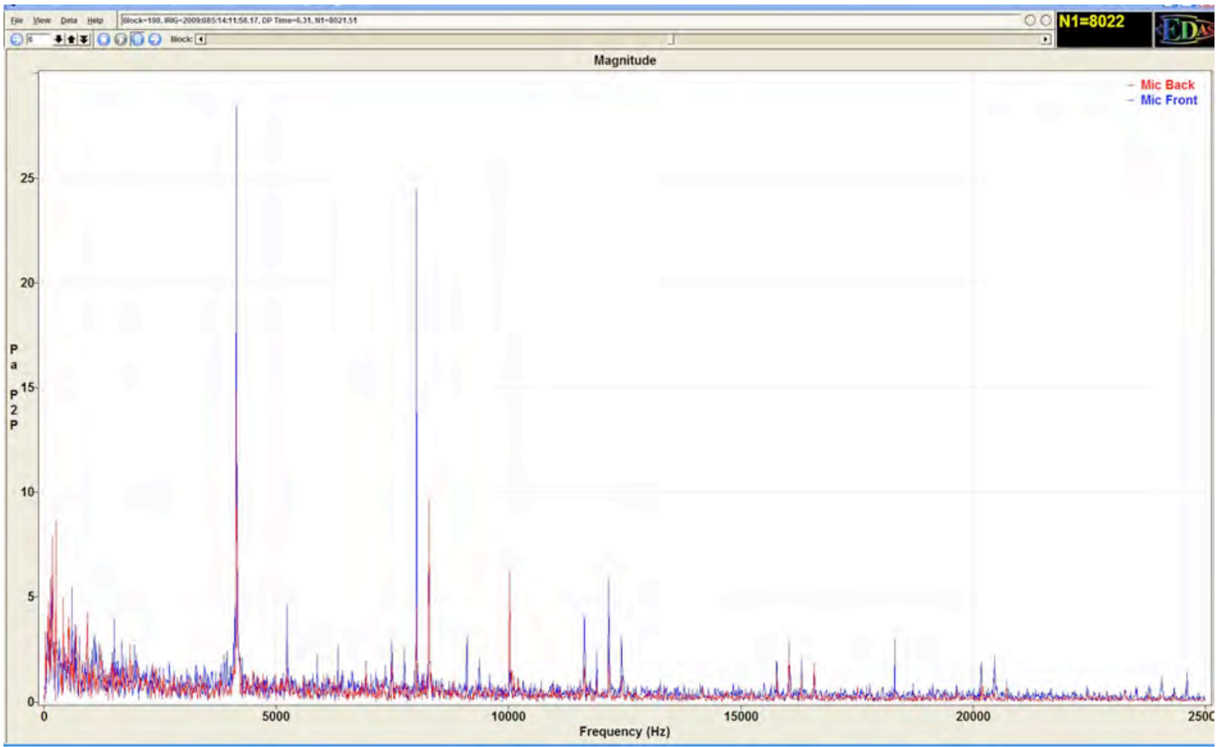

Figure 8a: FFT of Front and Back Microphones at Idle

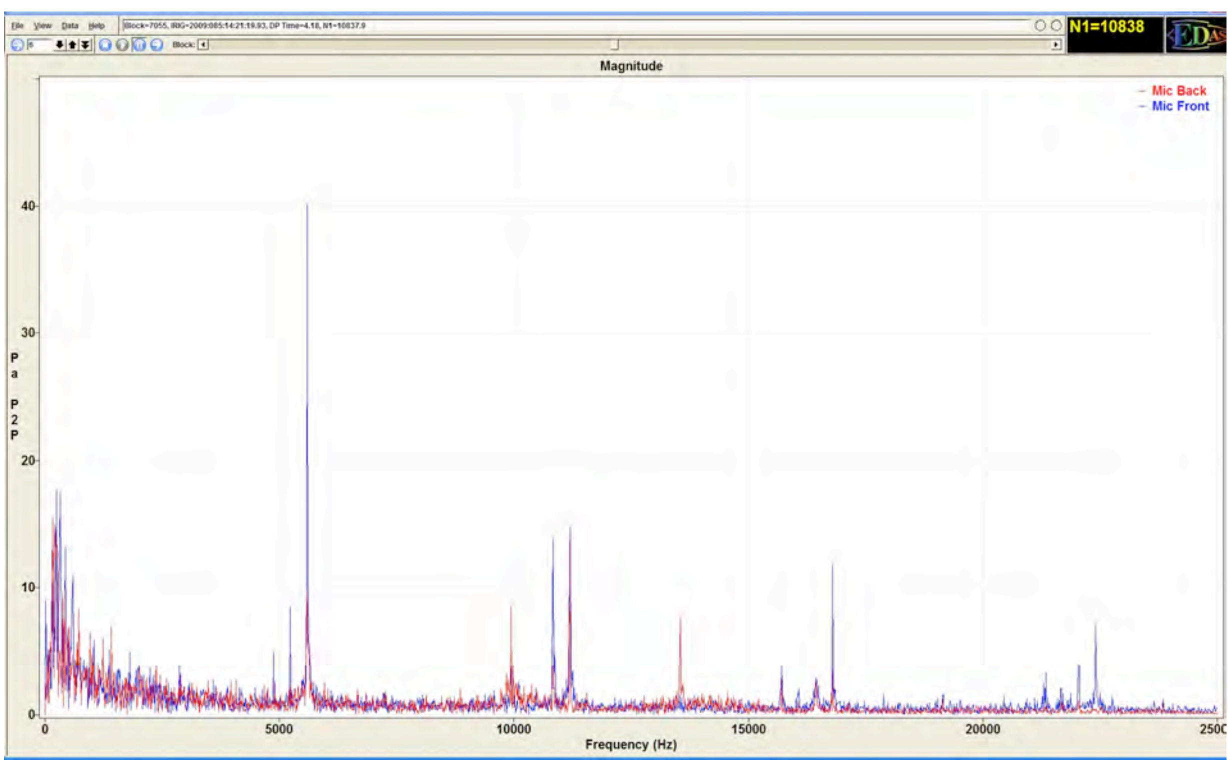

Figure 8b: FFT of Inlet Front and Back Microphone at 65%

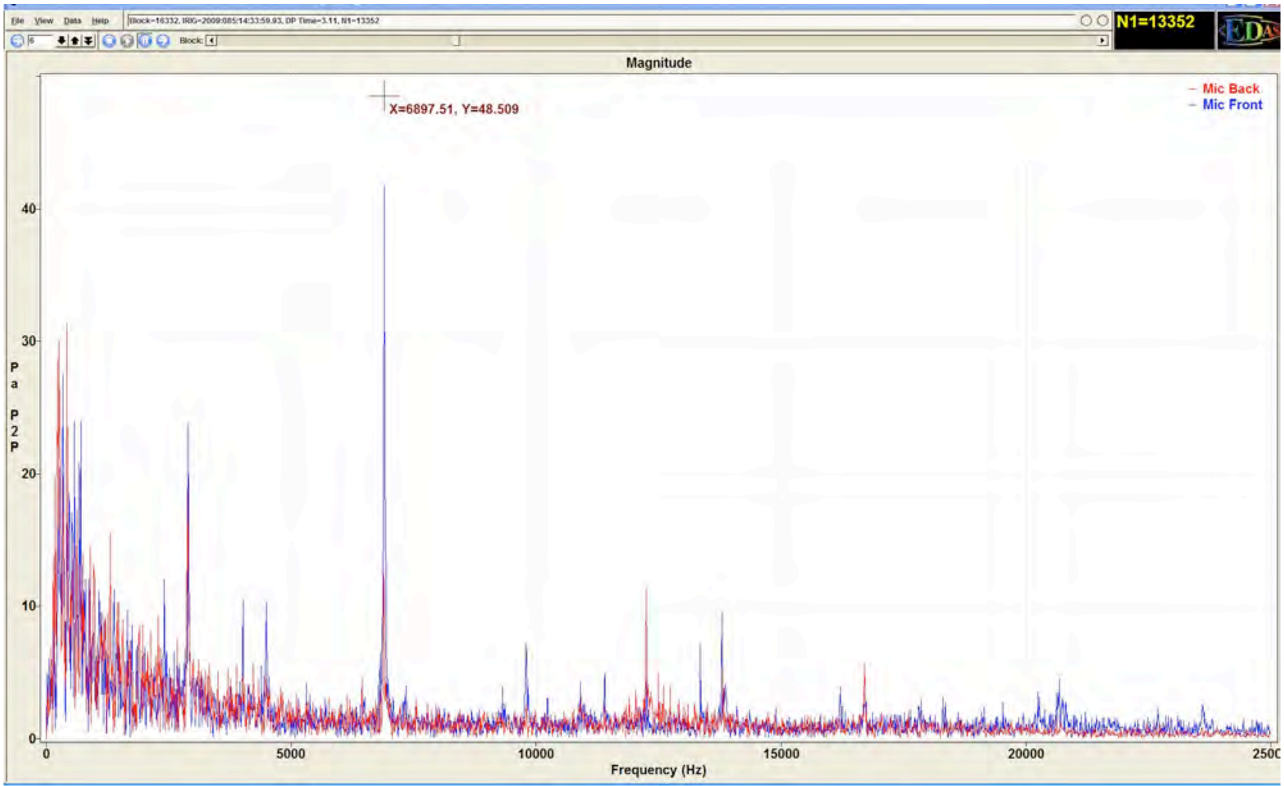

Figure 8c: FFT of Front and Back Microphone at 80%

Transient operations are also important opportunities for characterizing engine condition. The conventional waterfall plot of a ten second transient acceleration is shown in Figure 9. With this level of processing, there are no apparent structural resonances and the harmonics associated with the main engine rotor speed are observed throughout the acceleration.

Audio sensor fault implantation results

With the fuel nozzle fault and the seal rub test, the spectra across the power range of the engine showed no significant changes when compared to the baseline except for minor amplitude changes. Some indication was confirmed for biases in the inlet guide vanes. Further signal processing approaches are planned

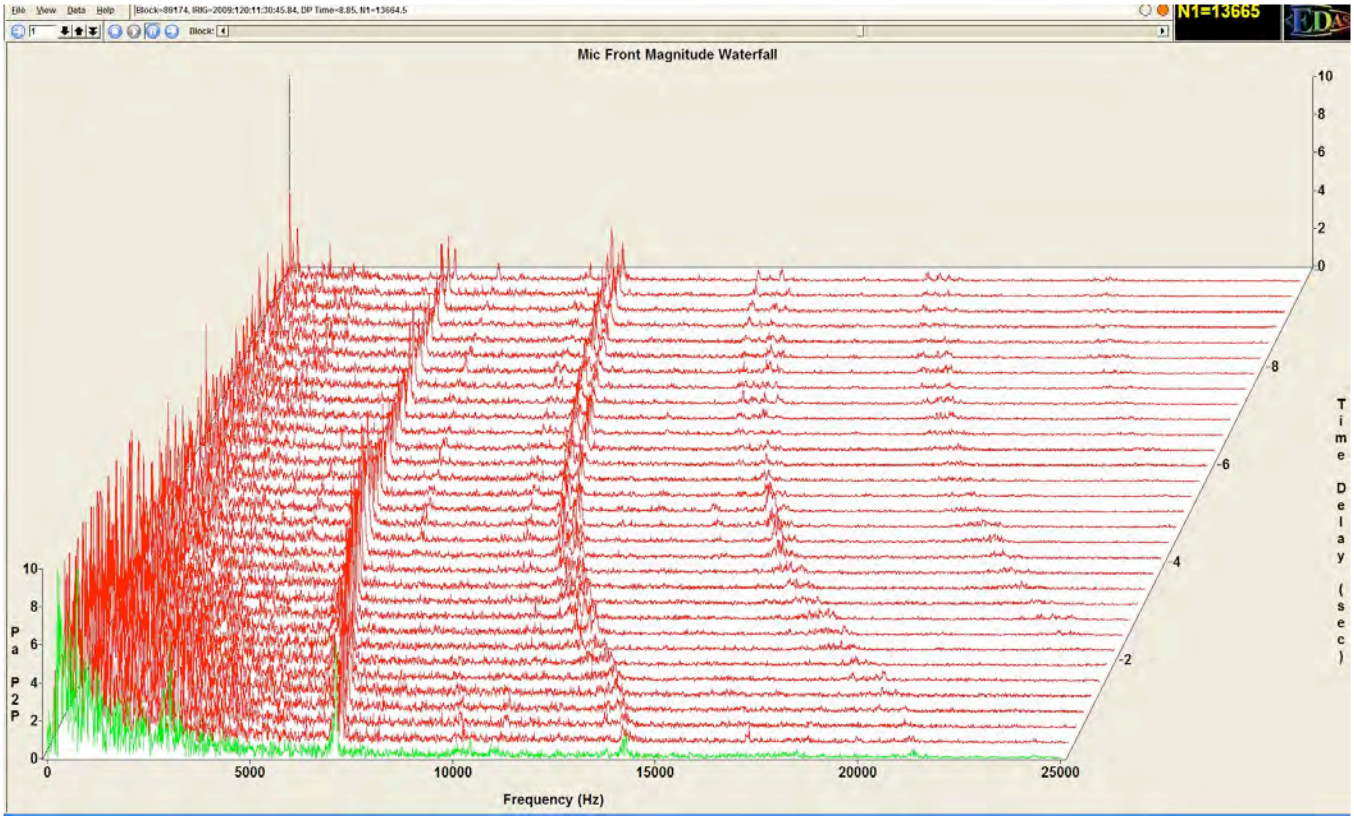

Figure 9: Waterfall plot of Front Microphone during acceleration from Idle to 80%

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 (Bird et al., 2007). As deterioration occurs, whether in a slow or a sudden event, voltage level changes have been correlated to real wear.

Electrostatic sensor baseline results

Modifications have been made to improve the sensor to give more consistent and reliable results. Baseline tests on the NRC turbojet engine used for the other sensors also included the electrostatic hoop. The hoop sensor was located at the rear of the engine around the tail pipe and outputs recorded for each engine power setting. Deviations from the baseline runs were then correlated with the implanted faults, i.e. turbine seal rubs and faulty fuel nozzle.

Figure 10 shows a comparison between electrostatic voltage output and engine speed, under baseline conditions. A fast acceleration from 72% to 85% engine speed is shown in this figure accompanied by an increase of electrostatic voltage. The increase would be consistent with the increase in airflow of 35 % which is thus correlated to a doubling of the voltage.

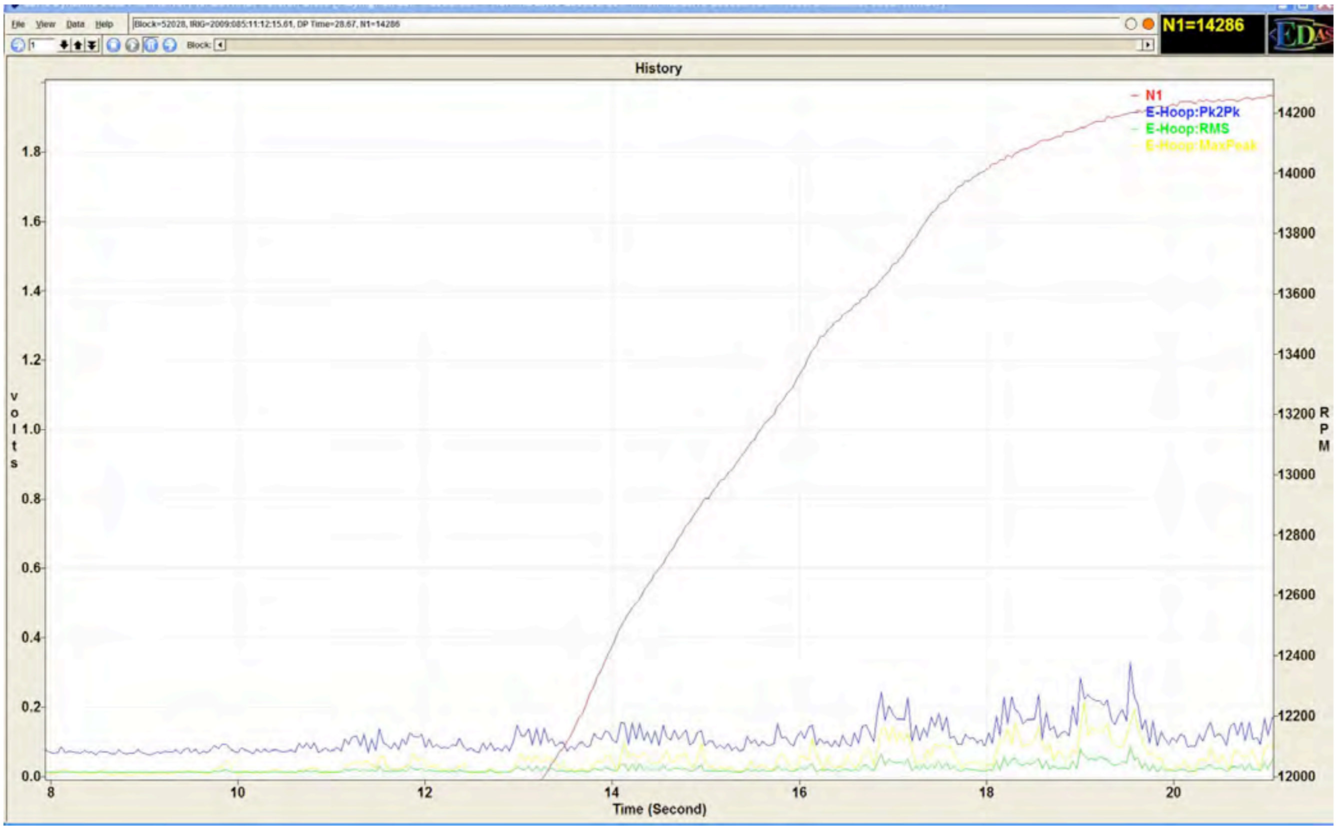

Figure 10: Comparison of electrostatic voltage to engine speed under baseline conditions

Electrostatic sensor fault implantation results

The turbine abradable seal was installed so as to induce a rub as engine rotor speed and temperature increase. Figure 11 shows the same conditions as shown in Figure 10, except under rub conditions. As engine speed was increased from 72% to 85% a rub occurred at about 8 seconds lasting for one second, which is easily seen in Figure 11. It was also noticed that as the engine was stabilizing thermally, along with some minor rubbing, another significant rub occurred at about 16 seconds.

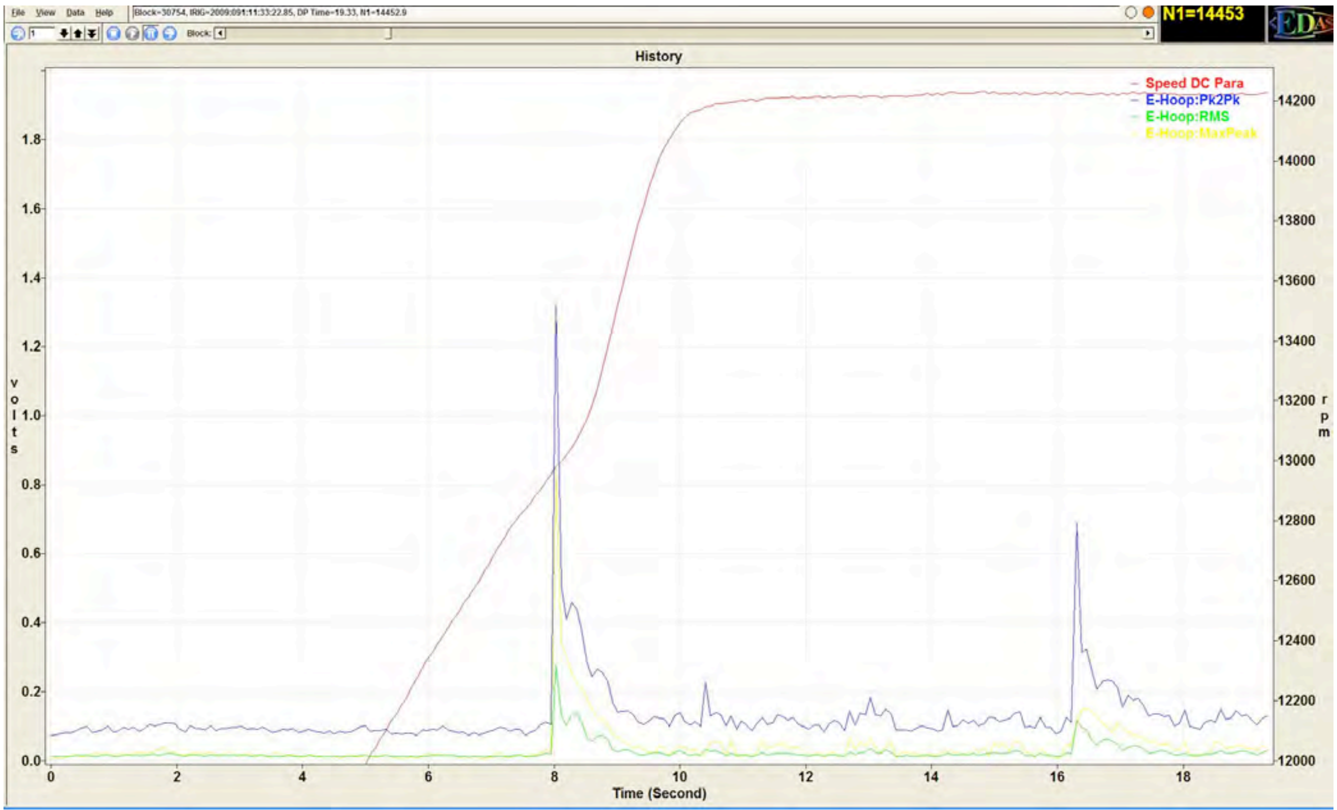

Figure 11: Comparison of electrostatic voltage to engine speed during blade rub conditions

For the fuel nozzle fault, some variations could also be observed with the electrostatic sensor. Figures 12 to 14 show the dc voltage bias for three different nozzle flow configurations for steady state data taken at three different power settings. The unsteady variation in engine rotor speed and airflow are observed in the width of the signals but the approximately 15% variation in amplitude is yet to be explained. The difference in average magnitude of the reading from the open to closed nozzle is only about 1%. It is postulated that the nozzle changes did not alter the particle production of the combustion process.

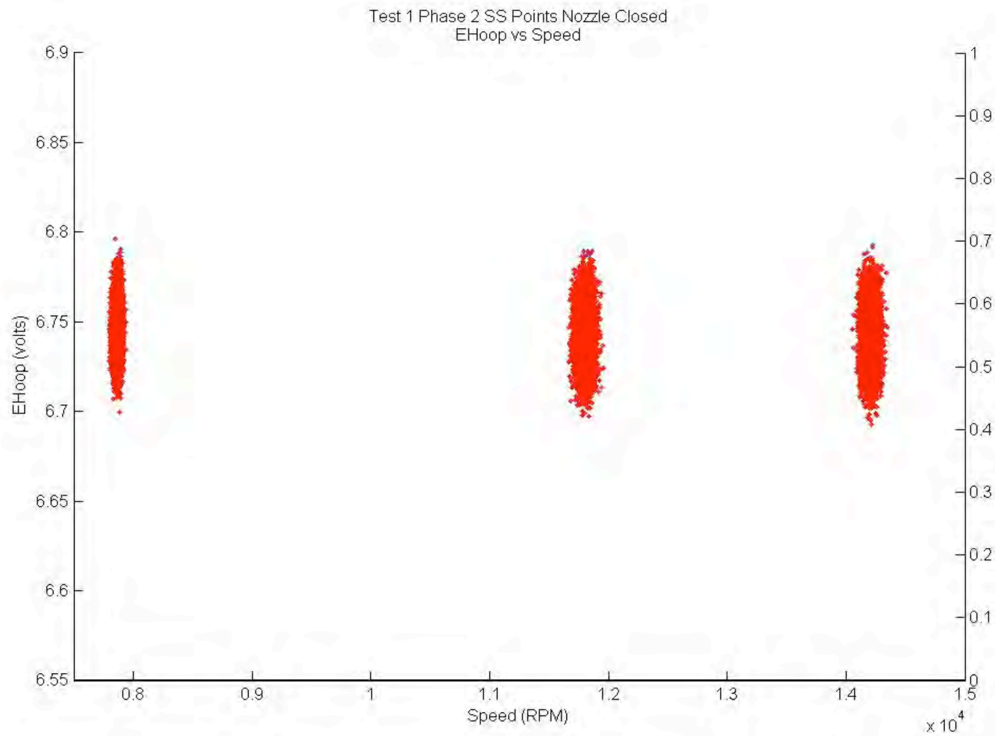

Figure 12: Electrostatic sensor output: closed nozzle configuration

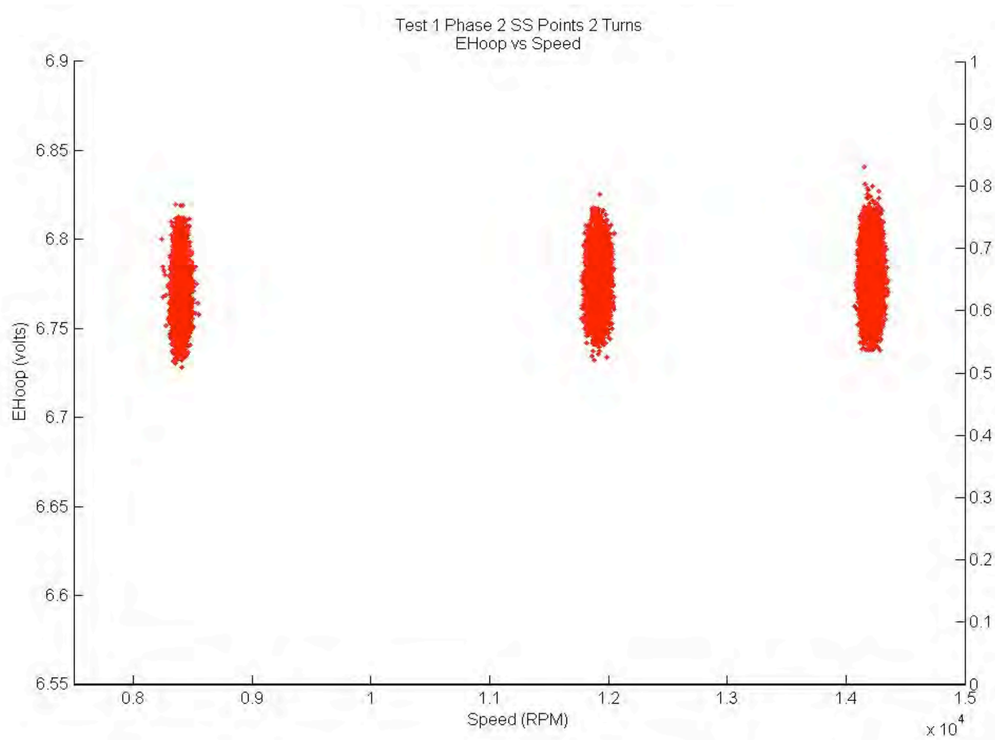

Figure 13: Electrostatic sensor output: partially closed nozzle configuration

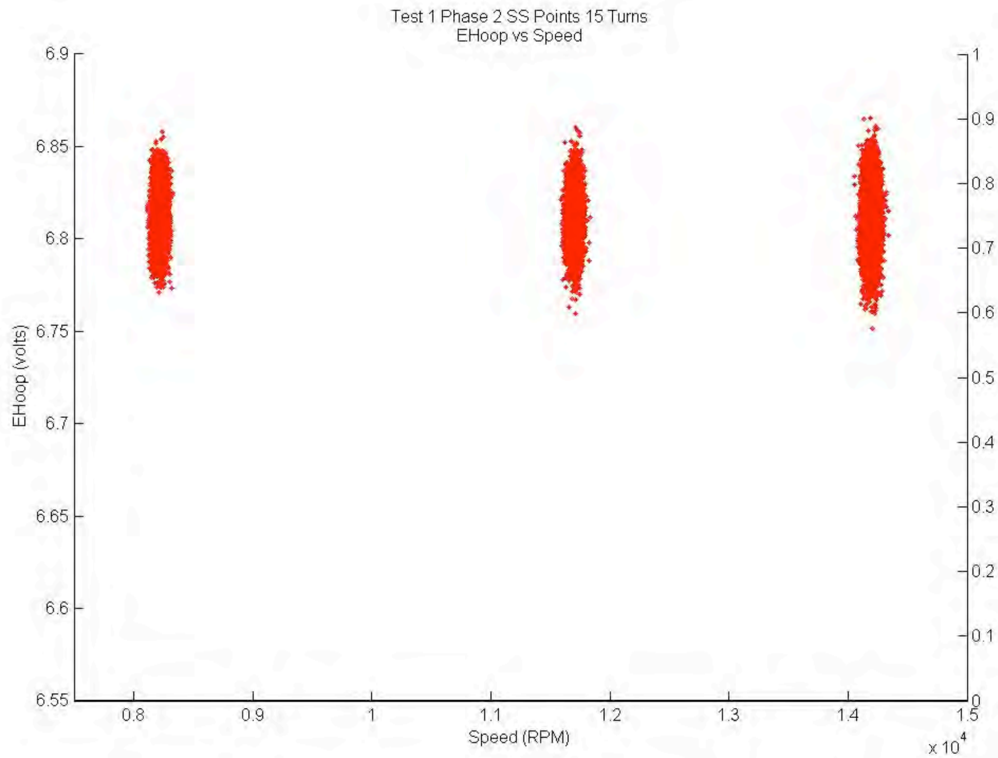

Figure 14: Electrostatic sensor output: open nozzle configuration

Spectroscopy

While the combination of infrared sensor and electrostatic sensor will identify the conditions for damage and the presence of particles, the source of the damage must be identified to plan maintenance or alter operations. Spectroscopy offers the means to identify the elemental composition of the particles (or gases) in the engine flows. The goal is to have accurate real-time indicators to warn engine or facility operators of a problem developing, the source and preferably the severity, e.g. to identify engine degradation that occurs over time.

Spectroscopy progress and plans

Earlier work had sampled engine exhaust following an induced turbine rub to successfully detect nickel through off-line processing. The rub event was clearly isolated during the 10+ minute test period with no material detected afterward (Bird et al., 2007).

An on-line Laser Induced Breakdown Spectroscopy (LIBS) system is currently being commissioned for gas turbine applications. A test chamber has been built and used to optimize the signal strength by varying optics, cables and lenses. The methodology and equipment are capable of static and transient sampling. Figure 15 shows the laser with a simulated beam focused on the sampling point with the detector mounted on a swivel head.

Bench tests with different metal powders (Ti, Al, Fe) have been promising. Figure 16 shows the results for a multiple injection of titanium powder. The software is set up to identify the detected wavelengths and the possible elements corresponding to these lines (inset table). The other inset is a waterfall style plot that shows multiple, repeatable spectra obtained at approximately 15 Hz.

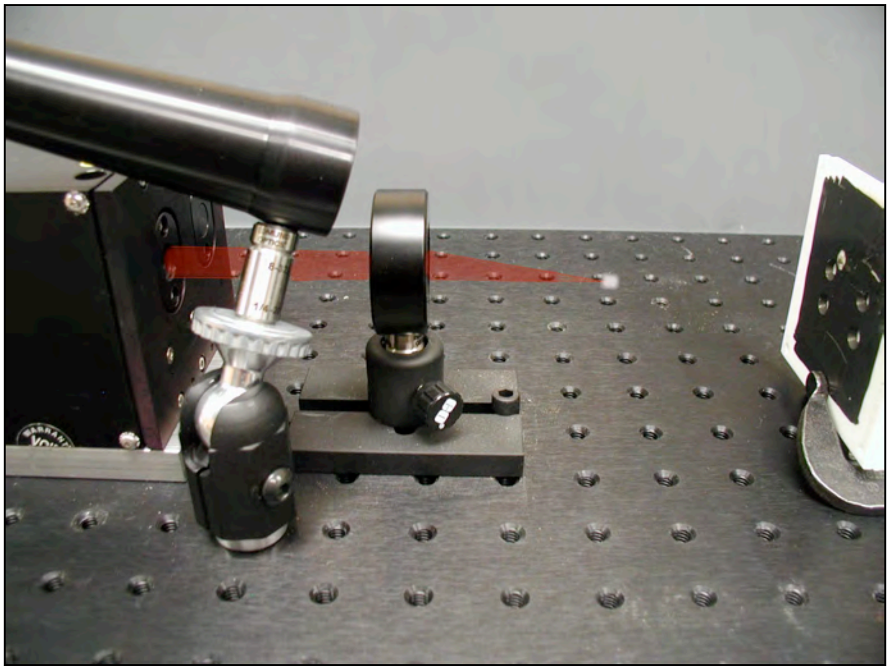

Figure 15: View of simulated LIBS operation

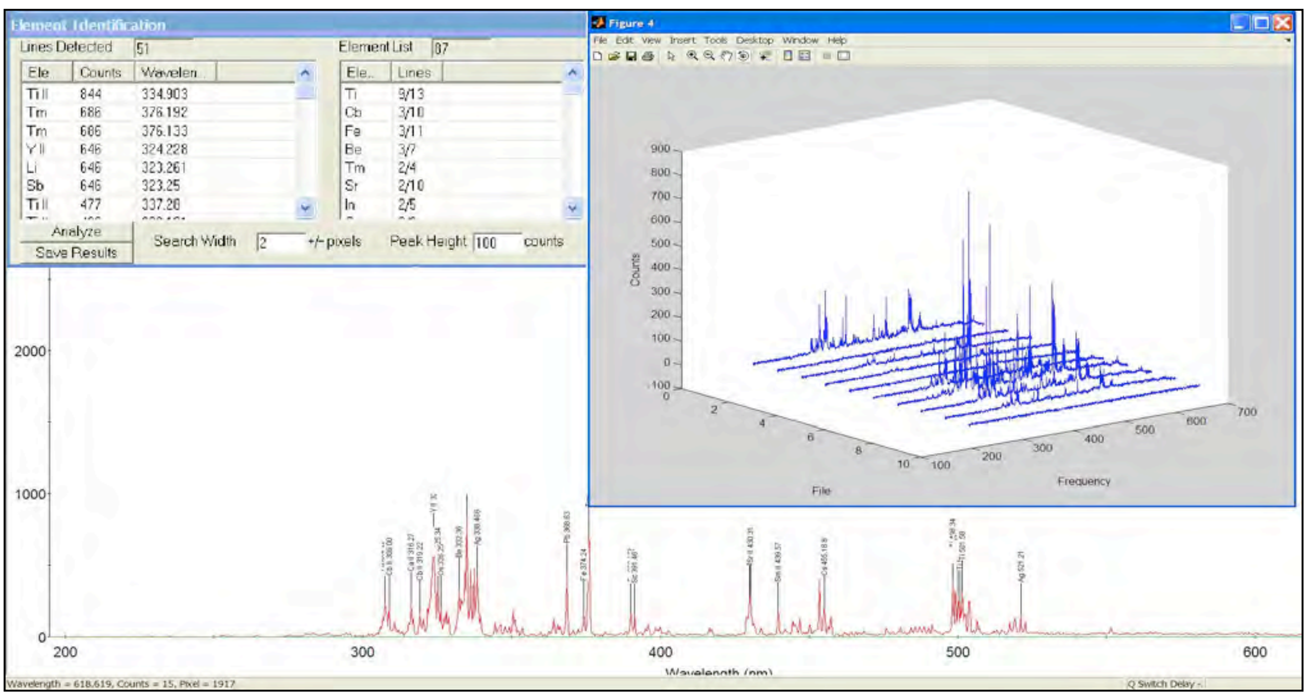

Figure 16: Spectroscopy identification of sequential titanium powder samples

Actual T56 compressor and turbine blades and stators were obtained. Methods were developed to identify T56 compressor and turbine constituent materials in service-exposed model A15 and A14 blades. Ti, Ni, Cr and Al were identified in combination in a sample blade and as a powder similar to what might be found in the exhaust flows of a damaged engine. The material 'fingerprints' of compressor and turbine blades were clearly distinguishable. (Figure 17 and 18)

Figure 17 shows a spectrum of a T-56 compressor blade. Strong and multiple iron (Fe) and chromium (Cr) lines are detected which are indicative of the blade alloy.

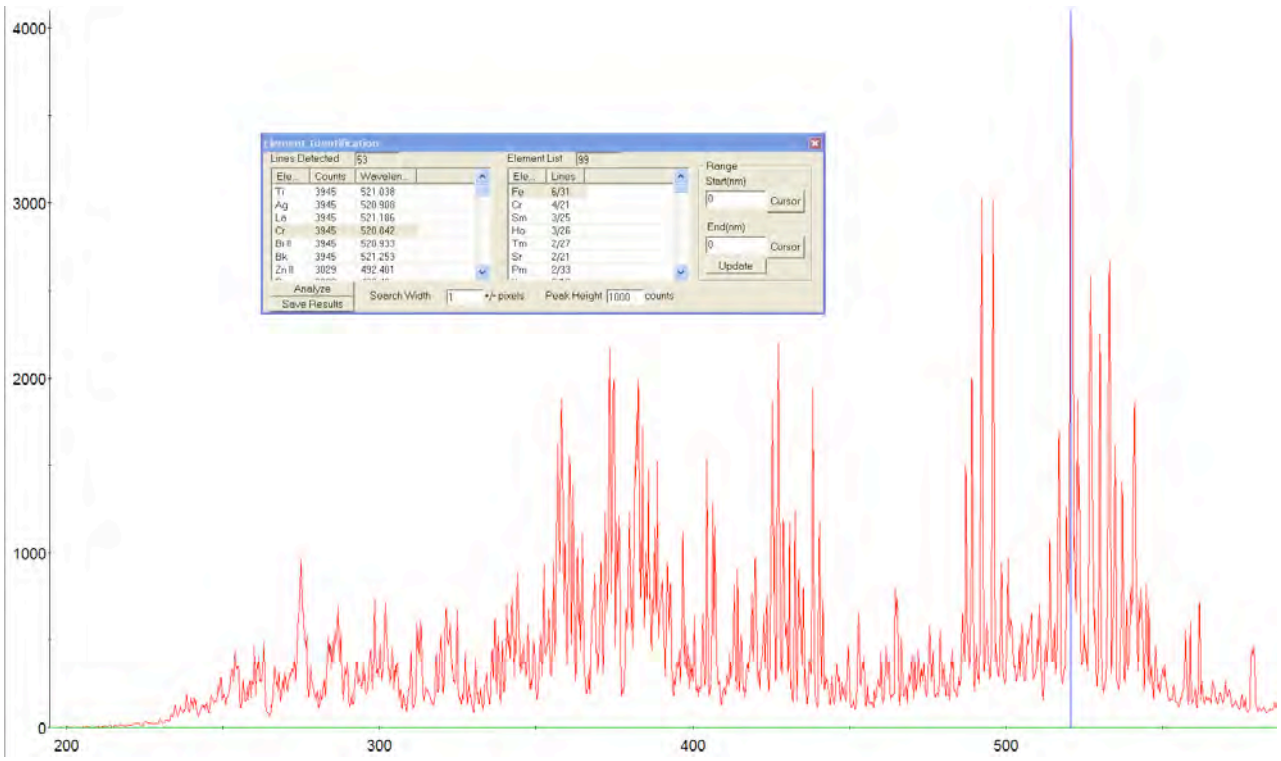

Figure 17: Spectroscopy identification of a T-56 compressor blade

Figure 18 shows a spectrum from a T-56 turbine blade. Strong nickel (Ni), chromium (Cr), aluminum (Al) and titanium (Ti) lines (inset table) were detected which are consistent with the blade alloy constituents.

In summary, the fast sampling rates and multiple metal detection capabilities of the LIBS systems have been confirmed. The applicability to real engine alloy material samples has been demonstrated.

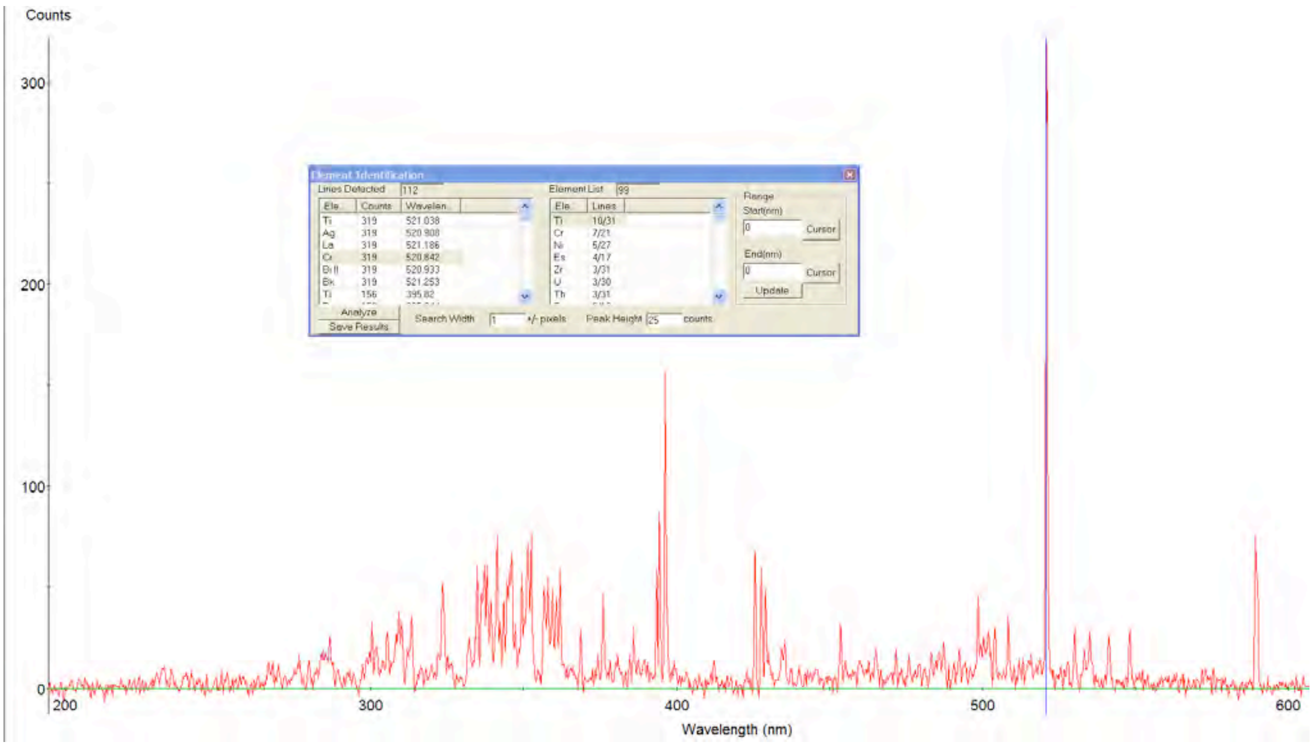

Figure 18: Spectroscopy identification of a T-56 turbine blade

Data Fusion

Effective engine health management is expected to require monitoring results from more than one functional area (gas path, performance, vibration, oil) to make the most informed operations or maintenance decision. 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.

Previous reports compiled progress and challenges (Bird et al., 2007). The system under development allows an analyst to visualize and conduct qualitative and quantitative studies of multiple sensor data. For example, exhaust infrared image presentations and analysis can be viewed with exhaust gas temperature performance graphs and data. Both pre-selected and investigative presentations are possible with the developer concentrating on quantitative results and synthesis of information and not data manipulation.

The provision of multiple sensors might be done in a cost effective way by adding non-intrusive sensors to conventional instrumentation. To investigate this approach, acoustic and vibration data were compared for the same test point. Figure 19 shows excellent agreement with key spectral features at 4126, 7996 and 9985 Hz for a healthy engine. Differences observed suggest that the audio signals can detect blade harmonics more easily and the vibration signals can identify rotor frequencies and their corresponding harmonics. The vibration signals may also pick up resonances in the engine which were not seen at all in the audio spectra.

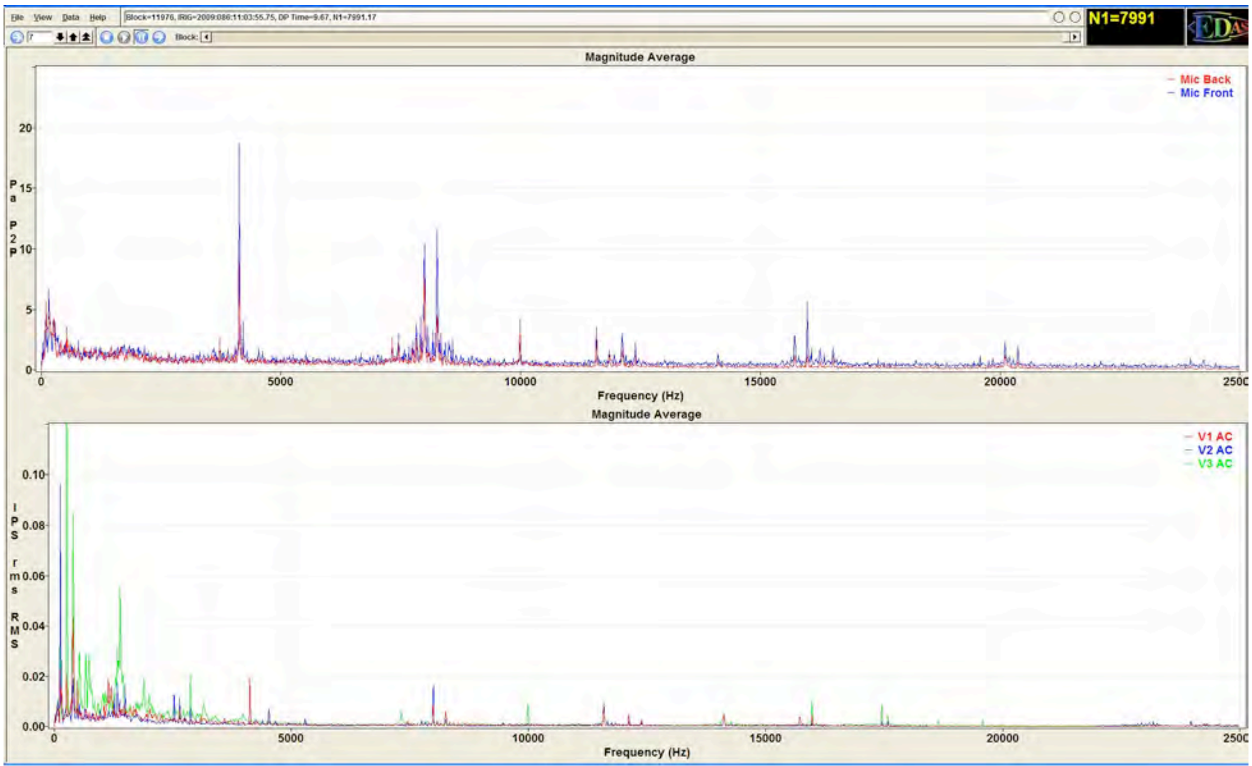

Figure 19: Data comparison for vibration and audio signals

Discussion

Sensor development is a means to an end; it should emphasize the direct contribution to reliable decision support systems for use by operators. The sensors described and demonstrated in this paper offer information on the condition of important engine components and the location of degradation directly. The tests conducted offer some clear evidence of the correlation of damage to measureable data for relevant faults. Associated data analysis and visualization tools have also been developed to allow ready use of the acquired engine data.

Opportunities exist for operators to participate. They can provide input on key operating conditions and degradations of concern, especially when these conditions may be novel or somehow unique to their operations. Particularly for non-intrusive systems, operators might provide access to field trials for transition and maturation of technologies proven in a test cell environment. Opportunities are needed to investigate the common features of faults within an engine fleet and across engine models.

Future plans

Technology evaluation will continue to focus on audio, IR, and electrostatic sensors with spectroscopy being transitioned to a wind tunnel rig and then to the test cell. Other applications are of interest if they support other maintenance or operational decision support issues that operators might identify. For example, anything that could be ingested into the intake of the engine, compressor and turbine rubs and carbon shedding should all be detected by the electrostatic sensor and may be isolated by the spectroscopy system.

A small wind tunnel and a sensor chamber are currently being designed and built to assess the capabilities of the current test bench designs. Conditions will be created to simulate actual engine conditions, velocities and concentration levels observed in the field. Analysis and optimization of the systems during this phase will determine the sensitivity and threshold detection levels as well as modifications needed to apply this sensor in a test cell.

Conclusions and Opportunities

This report has provided some documentation of the capabilities of non-intrusive sensors and analysis techniques to contribute to enhanced condition monitoring by users. Additional information for decision support is possible on engine performance and especially component condition, all with limited impact on the engine-specific installation. Sensors can be added to the facility without modification to the engine. The objective is to develop a prototype 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 and isolation 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 ongoing at NRC to spur development of practical sensor and health management technology. The CF700/J85 turbojet engine and T400 turboshaft are being used at the Gas Turbine Lab to gather sensor suite data with implanted faults in a test cell setting. DRDC and NRC are continuing to work together on a new project to demonstrate and evaluate integrated vehicle health management technologies. This work will involve development and use of available bearing, engine, structures and seal rigs. In addition, specialized sensor simulation chambers will be constructed to duplicate pressure and temperature levels and transients found in engines.

Additional opportunities are sought from industry and users to define needs, test plans and add prototype sensors to existing installations. The goal would be to compile operating experience and assist in the transition of technology to the field.

Partnerships

Government-industry forums like the IAGT are seen as important opportunities to define needs and showcase appropriate technology. Several similar 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.

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Work on this cooperative/open source capability for diagnostics development and evaluation continues. The broad-based initiative was started 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 (Jaw, 2005). The current theme problem on gas path diagnostics has progressed to the development of an engine fleet simulation tool where faults, noise and operational variations may be selectively incorporated (Simon et al., 2008). While the current application is to an aircraft turbofan the methodology and approach might be extended to the industrial field. Other theme problems of vibration analysis, oil/debris monitoring and usage and life monitoring themes have also been proposed. International cooperation and participation are being lead by The Technical Cooperation Program, for which the NRC Gas Turbine Laboratory is the current point of contact.

Others

The Society of Automotive Engineers sponsors a working committee E-32 on Aerospace Propulsion System Health Management [SAE, 2009]. The projects in progress or under consideration include: Software Interface for Ground-Based Monitoring, Health and Usage Monitoring System (HUMS)- Accelerometer Interface Specification, HUMS-Rotational System Indexing Sensor Specification, HUMS- Blade Tracker Interface Specification, HUMS- Advanced Multipoint Interface Specification, Guidelines for software certification of EHM systems, Lessons Learned from Developmental and Operational Turbine Engine Monitoring System, Guide to Temperature Monitoring in Aircraft Gas Turbine Engines, Health Monitoring Cost Benefit Analysis, Compressor Airfoil Diagnostics, Use of the In-System Filter to Support Condition Based Maintenance and Validation and Verification of EHM Signal Analysis Capabilities. Industry involvement is strongly encouraged.

Acknowledgements

Jim MacLeod is acknowledged for his vision and hard work for initiating a number of the early studies in non-intrusive sensors in the Engine Lab of NRC. Michael Mulligan was instrumental in the early development and application of the infrared work. Defence Research and Development Canada provided many years of financial and moral support.

Structures and Materials Performance Laboratory (SMPL) for their donation of T56 engine components. A number of research assistants have made dedicated efforts to advance this work including Peter Steckhan, Dawn Layton, Jennifer Chalmers, Anthony Soung Yee, Niels Roth, and Stephen Chee.

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Biographies

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