

# Development and Testing of Propulsion Health Management

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**Abstract**—An Integrated Vehicle Health Management system aims to maintain vehicle health through detection, diagnostics, state awareness, prognostics, and lastly, mitigation of detrimental situations for each of the vehicle subsystems and throughout the vehicle as a whole. This paper discusses efforts to advance Propulsion Health Management technology for in-flight applications to provide improved propulsion sensors measuring a range of parameters, improve ease of propulsion sensor implementation, and to assess and manage the health of gas turbine engine flow-path components. This combined work is intended to enable real-time propulsion state assessments to accurately determine the vehicle health, reduce loss of control, and to improve operator situational awareness. A unique aspect of this work is demonstration of these maturing technologies on an operational engine.

**Index Terms**—Sensors, algorithms, engine, high temperature, electronics, gas path, smart sensors

## I. INTRODUCTION

AN Integrated Vehicle Health Management (IVHM) system aims to maintain vehicle health through detection, diagnostics, state awareness, prognostics, and lastly, mitigation of detrimental situations for each of the vehicle subsystems and throughout the vehicle as a whole. Major subsystems associated with a vehicle wide IVHM system are the airframe, avionics, and propulsion systems. Overall, such an IVHM system aims to maintain the health of a structure through diagnostics, state awareness, prognostics, and lastly, mitigation of a detrimental situation associated with the various subsystems as well as the vehicle as a whole. Each subsystem has its own challenges associated with development of IVHM technologies.

One particular challenging subsystem for vehicle health management is related to propulsion health management. The engine is a complex system with a range of operating components whose failure can affect passenger safety. Reliable operation of these engines is critical for aircraft safety. The harsh environment conditions within an engine often present significant challenges for the integration and application of health management systems. In parallel, diagnostic systems often have to perform evaluations with limited sensor information, while evaluating a complex system whose components include gas path, turbomachinery, hydraulics, and other components.

This paper discusses efforts to advance Propulsion Health Management technology for in-flight applications to provide improved propulsion sensors measuring a range of parameters, improve ease of propulsion sensor implementation, and assess

and manage the health of gas turbine engine flow-path components. The emphasis in this paper will be on the sensor technology development, but also includes algorithm development. The combination of both sensor systems and algorithms is necessary to enable real-time propulsion state assessments to accurately determine the vehicle health, reduce loss of control, and to improve operator situational awareness. It is this combined approach that is planned for future demonstration on operational engine systems.

## II. HARSH ENVIRONMENT ENGINE SENSOR TECHNOLOGIES

Information generated by sensors is the foundation of an IVHM system. The propulsion sensor development considers the complete sensor system including the overall need to reduce sensor size and weight, the need to improve sensor reliability, and the need to increase the availability of sensor information [1]-[3]. The technologies being developed include multiple sensors for the identification and assessment of degradation throughout the engine as well as advanced analytical techniques that both complement the sensor technology and also provide improved capability for detecting anomalies in propulsion data. The sensor technologies being addressed include:

- Self Diagnostic Accelerometer
- Microwave Blade Tip Clearance Sensor
- High Temperature Fiber Optic and Thin Film Temperature Sensors
- Emission Sensors
- High Temperature Wireless Sensors

In the following sections, general descriptions, current activities and future plans for each of the propulsion sensor technologies are provided. An effort is made to provide a description of relevance as well as baseline performance considered in terms of flight or flight ready technology.

### A. Self Diagnostic Accelerometer

Accelerometers are commonly utilized for structural health monitoring of both aircraft and spacecraft engines [2], [4]. Accelerometers generally monitor machine health by monitoring vibration measurements in a particular frequency band for exceedance of acceptable vibration magnitudes and rotor-out-of-balance conditions. The Self Diagnostic Accelerometer (SDA) is an electronic diagnostic system that monitors the accelerometer sensor. This system identifies changes in temperature, sensor loosening, and sensor structural or electrical damage [5]-[11]. Real-time sensor validation is necessary to prevent a vehicle controller or facility safety

system from making critical decisions, such as the decision to shut down an engine or abort a launch, on the basis of anomalous sensor data [12],[13].

The purpose of this technology is to provide a real time method of sensor validation that can be utilized as part of a propulsion structural health management system to improve overall reliability of engine health assessment. The SDA system, diagrammed in Fig. 1, monitors the accelerometer health by sending a frequency swept sinusoidal signal to its piezoelectric crystal and concurrently monitoring the accelerometer's frequency response, or diagnostic signal. Sensor failures show up as shifts in the resonant frequency of the accelerometer. Sensor changes observed are correlated to predefined parameters that determine sensor loosening, and sensor structural or electrical damage, while compensating for shifts caused by temperature change. In the case of sensor disconnection, there are no resonances. Sensor detachment results in resonant frequency shift, while sensor damage results in additional sensor resonant frequencies.

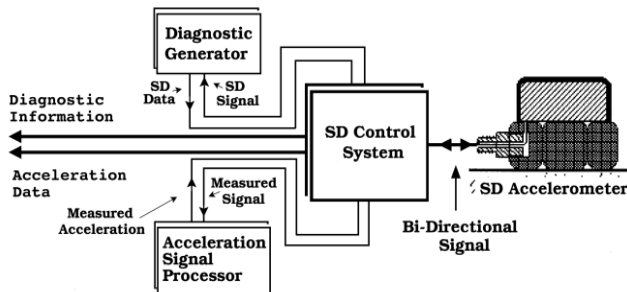


Fig. 1. Data Flow Diagram of SDA system. The diagnostic signal frequency is outside of the measured signal frequency band.

The SDA system has been tested to gauge its performance in simulated engine operating conditions. The SDA system was investigated in detail to determine overall system efficacy in anticipated typical engine operating temperatures and vibration levels. The real time results of such testing successfully demonstrated the autonomous SDA system in a simulated engine environment. Future work includes development of the next generation SDA system prototype, with added capabilities, faster processing, and more memory.

### B. Microwave Blade Tip Clearance Sensor

The development of structural health monitoring schemes in turbine engines requires sensors that are highly accurate and can operate in a high temperature environment. Microwave sensor technology is being investigated as a means of making non-contact structural health measurements in the hot sections of gas turbine engines. This type of sensor is beneficial in that it is accurate, it has the ability to operate at extremely high temperatures, and is unaffected by contaminants that are present in turbine engines. It is specifically being targeted for use in the High Pressure Turbine (HPT) and High Pressure Compressor (HPC) sections to monitor the structural health of the rotating components. In particular, blade tip clearance measurements can be used to monitor blade growth and wear, and blade tip timing to monitor blade vibration and deflection [14].

The evaluation of microwave blade tip clearance sensors for

use in propulsion health monitoring is currently being conducted. The microwave sensors being investigated were developed as part of NASA's Small Business Innovation Research (SBIR) Program along with other research and development contracts. These sensors operate at 5.8 GHz and were intended for use in large land based power generation turbines. Subsequently, a 24 GHz blade tip clearance system and several second generation probes were delivered as part of a follow-on commercial contract. These probes are being targeted for use in aero turbine engine applications.

Experimentation has shown that the microwave blade tip clearance sensor technology is a viable option for propulsion health monitoring applications [15]. Both the first and second generation sensors have been successfully demonstrated on rotating machinery and other aero engine hardware. The first generation 5.8 GHz sensors were used on a large Axial Vane Fan and a NASA Turbofan to acquire blade tip clearance data. The second generation 24 GHz sensors were used to make basic blade tip deflection and low range clearance measurements on a simulated engine disk that had pre-bent blades. The second generation sensors were also calibrated and used on a small compressor disk on a calibration spin rig. The results achieved so far have been positive. It is planned to continue the blade tip deflection experiments in order to refine the sensor's deflection measurement capability.

### C. High Temperature Fiber Optic Sensors

The high temperature fiber optic research is targeted towards providing expanded sensor coverage of sensed parameters through the use of fiber optic technology to provide robust and reliable measurement in hot sections of the engine. There are multiple potential advantages of optical fiber sensors. For instance, optical devices are immune to the effects of electromagnetic interference and therefore do not need electrical insulation. This makes the sensors well suited to work in electrically charged environments and in such locations where electrical discharge may be an issue. The sensors also have significant chemical immunity to permit operations in a harsh environment. Furthermore, the small diameter of the fiber permits easy embedding within structures. It is also anticipated that optical fiber sensors will have improved integration capability because multiple sensors can be put on a single fiber and there is no need for separate power wires.

The development of high temperature optical thermal sensors initially focused on non-packaged devices, which simply consisted of optical fibers with Fiber Bragg Gratings (FBG) written into the fiber. Experiments with these high temperature fiber optic sensors have demonstrated the long term survivability of FBGs at temperatures up to 1000°C through many thermal cycles. In these tests, the fiber optic sensors underwent 400 hours of thermal cycling up to 750°C and 700 hours of thermal cycling to 1000°C.

Recent research has been focused on constructing and evaluating the performance of packaged sensing devices at temperatures above 1000°C and with high thermal heating rates. A process of manufacturing high temperature FBG-based sensors has been developed and demonstrated. The process has permitted construction of robust packaged sensing

devices capable of withstanding extreme temperatures.

Future efforts in this area will initially focus on evaluating the durability of the packaged FBG sensors at 1000 °C for longer durations of time. Once the sensors are proven stable for such a length of time, the sensors will then be evaluated for response to thermal shocks as well as vibration and nominal mechanical testing.

#### D. High Temperature Thin Film Sensors

Development of thin film sensors for surface measurement in critical vehicle health monitoring applications for future space and air vehicles propulsion systems has included sensors for strain, temperature, heat flux, and surface flow [16],[17]. The current challenges of instrumentation technology are to further develop specialized sensor systems, further develop instrumentation techniques on complex surfaces, improve sensor durability, and address needs for higher temperature applications exceeding 1500 °C. The use of sensors made of thin films has several advantages over wire or foil sensors. Thin film sensors do not require special machining of the components on which they are mounted, and with thicknesses less than 10  $\mu\text{m}$  they are considerably thinner than wire or foils. Thin film sensors are thus much less disturbing to the operating environment, and have a minimal impact on the physical characteristics of the supporting components. A broad array of thin film physical sensor technology is being developed.



Fig. 2. A thin film multifunctional sensor in the geometry of an off-axis rosette.

One example is a thin film multifunctional sensor, which integrates into one "smart" sensor structure the designs of individual gauges that measure strain magnitudes and direction, heat flux, surface temperature, flow speed and direction [18], [19]. The entire gauge is microfabricated, enclosing a triangular area approximately 1.5 cm on a side with 50- $\mu\text{m}$ -wide features, and is shown in Fig. 2. Designed for applications in material systems and engine components testing, the sensor can provide minimally intrusive characterization of advanced propulsion materials and components in hostile, high-temperature environments, validation of propulsion system design codes, and experimental verification of computational models. Various prototypes of the gauge have been bench tested on alumina substrates [19]. Future testing will include measuring all of the parameters simultaneously on a component to be tested in an engine environment, as well as increasing the operating temperature of this and other physical sensor systems.

#### E. Emissions Sensor Array

The detection of the chemical signature of the emissions of a propulsion system is understood to reflect the efficiency and

health of the system. Rapid or sudden changes in the emissions produced by combustion indicate changes in the propulsion system combustion process or engine health state. Ideally, an array of sensors placed in the emission stream close to the propulsion system could provide information on the gases being emitted by the propulsion system. However, there are very few sensors available commercially that are able to measure the components of the emissions in-situ since the harsh conditions and high temperatures of the propulsion system render most sensors inoperable. Thus, in order to detect the other species present in an emissions stream, the development of a high temperature chemical sensor array technology is necessary. Such a gas sensor array would, in effect, be a "high temperature electronic nose" and be able to detect a variety of gases of interest to monitor the health of the system producing those emissions.

Development of a gas sensor array (high temperature electronic nose) has been on-going related to engine teststand evaluation systems. Turbine engine exhaust emission measurements are frequently required during engine development ground test programs. In order to meet these needs, high temperature emission sensor technology has been developed previously [20]. This emissions sensor technology is based on gas microsensor arrays to quantify composition of critical constituents in turbine engine exhaust products, e.g., carbon monoxide, carbon dioxide, nitrogen oxide, and unburned hydrocarbons. Close coupling of the sensor and probe eliminate long sample transport distances. The response time of gas microsensor systems will be faster than typical gas analyzers by at least the sample transport time. Additionally, the cost of procurement of a high temperature electronic nose is expected to be an order of magnitude less expensive than current gas analysis methods.

Efforts are on-going to directly demonstrate the correlation of the response of this high temperature electronic nose to changes in engine health state (see Integrated Testing and Future Directions section below). In the future, this high temperature electronic nose system is intended to be integrated into the structure of an engine for on-board gas analysis for engine health monitoring, combustion efficiency and possibly even to control these emissions via feedback control.

#### F. High Temperature Wireless Sensor System

Currently, for almost every sensor, actuator, or processing unit implemented on an engine to improve the in-situ monitoring of the components, communication and power wires follow. The wires may be within or between parts, or from the engine to the controller/power source. Each sensor system added to the aircraft increases the number of wires and the associated weight, complexity, and potential for unreliability. Furthermore, wires and connectors are a main failure mechanism for the sensor systems.

Test stand engines are often heavily instrumented and the resulting sensors create a "spaghetti" of wires. This is shown in Fig. 3 [21], where a fully instrumented engine is shown on a test stand during a qualification procedure. The teststand instrumentation is sufficient to characterize the engine for qualification, but such extensive diagnostic capabilities are not available for in-flight operation due to massive weight and

complexity of the associated wiring among other reasons [22]. Overall, the current state of the art for the sensors and their associated wires is too great of a burden for practical use. The resulting engine has limited self-monitoring capabilities and thus limited diagnostic capabilities. This suggests the need for a stand-alone complete sensor system that can operate at high temperatures and be able to process and wirelessly transmit data enabling sensor implementation without generating a “spaghetti” of wiring and associated reliability concerns.

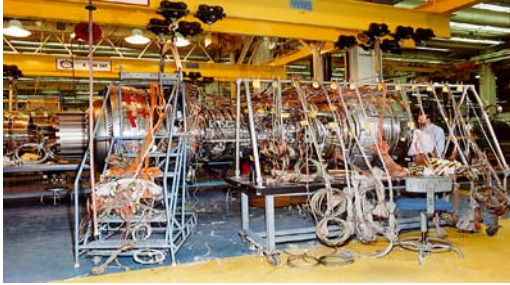


Fig. 3. Development engines require extensive instrumentation using wires and connections. Typically, 1300 wires are associated with instrumentation for a test stand characterization of an engine. Photo provided by the Propulsion Instrumentation Working Group [21].

One technology necessary to enable such a stand-alone system is the electronics that provide the processing and communication capabilities. However, the engine applications do not lend themselves to the use of standard silicon (Si) based electronics due to the high temperatures involved. An electronic material system such as silicon carbide (SiC), which has shown component operation to temperatures of 600°C [23], has the potential of meeting a range of engine application needs [24]-[25]. The development of SiC electronics has been on-going [26]-[27]. The thrust of the work has focused on showing the durability and viability of high temperature electronics at 500°C. Simple analog amplifier and digital logic gate integrated circuits fabricated and packaged by NASA have now demonstrated thousands of hours of continuous 500°C operation in oxidizing air atmosphere with minimal changes in relevant electrical parameters. This work has been record breaking in demonstrating durability and functionality of SiC electronics for harsh environment applications.

Future work in high temperature circuit development will be focused on increasing the complexity of these circuits for increased functionality and eventually leading towards high temperature wireless circuits. This includes the development of a wireless sensor node that will feature integration of a sensor, circuitry, and power system operable at temperatures up to 500°C. A wireless sensor system including signal conditioning, power harvesting, a pressure sensor, and wireless communication has been demonstrated at 300°C in preparation for higher temperature systems [28].

### III. GAS PATH DIAGNOSTICS

The overall Engine Health Management (EHM) system plays a critical role in assisting aircraft operators in managing the safety, reliability, availability, and affordability of gas

turbine engine assets [29]-[32]. The functionality provided by an EHM system includes deterioration trend monitoring, life usage tracking, diagnosis of engine faults, and providing recommended inspection and maintenance actions. The individual subsystems that comprise an EHM system vary by application, but generally consist of lubrication system health management, structural vibration monitoring, structural life usage tracking, and gas path health management. In particular, work has been on-going in developing Gas Path Health Management (GPHM) technologies.

The goal of GPHM is to reliably assess and manage the health of gas turbine engine flow-path components and controls accessories [33]-[34]. It is performed by relating observed changes in sensed engine variables to internal performance-related changes within the gas turbine engine cycle. Monitoring and processing engine sensed measurements enables the detection and isolation of problems, ultimately enabling corrective action to be taken. Examples of the types of events that can be addressed by GPHM include gradual component deterioration, sensor faults, actuator faults, and turbomachinery damage. Because GPHM provides a system level assessment of engine health, it is a cornerstone technology of an overall engine health management system.

GPHM primarily relies upon the gas path sensors installed on the engine for control purposes. Historically, GPHM came into prevalence concurrent with the introduction of digital engine controls and avionics. Prior to this, gas path performance trending was conducted manually based on cockpit gauge readings hand-recorded by pilots. The introduction of digital avionics and controls revolutionized this process by providing access to additional sensed measurements, along with automated data acquisition and processing capabilities. This enabled the inclusion of on-board engine diagnostic functionality, as well as ground-based fleet-wide EHM functionality in computer ground stations, which processes engine data acquired in-flight. Operators now rely on this combined on-board and off-board functionality to manage the health of their engine assets.

Continuing advancements in avionics are enabling more sophisticated on-board GPHM functionality. Towards that vision, a proposed enhanced GPHM architecture has been developed that incorporates on-board model-based diagnostic and performance estimation functionality [35]-[36]. The enhanced architecture gains real-time access to an expanded quantity of engine parameters and provides real-time continuous monitoring of engine health, the early diagnosis of fault conditions, and the estimation of unmeasured engine performance parameters that can be directly applied for health management and controls applications.

The enhanced architecture, like the previously discussed conventional architecture, contains both on-board and ground-based functionality. In fact, many of the components that make up the two architectures are identical. The primary difference is the inclusion of real-time on-board model-based GPHM functionality within the enhanced architecture. The inclusion of on-board models is an emerging practice in the aircraft engine industry. These models have the ability to self-tune to match the current performance level of the engine as it

degrades over time [37]-[39]. Current applications of on-board self-tuning engine models are largely for sensor validation. The future vision is to expand the utility of such models for use in engine diagnostics and to provide more accurate estimation of unmeasured engine parameters to support advanced model-based controls and life usage monitoring applications. The proposed enhanced GPHM architecture that leverages on-board model-based technology is shown in Fig.4. The enhanced functionality included in the architecture is outlined by dashed boxes.

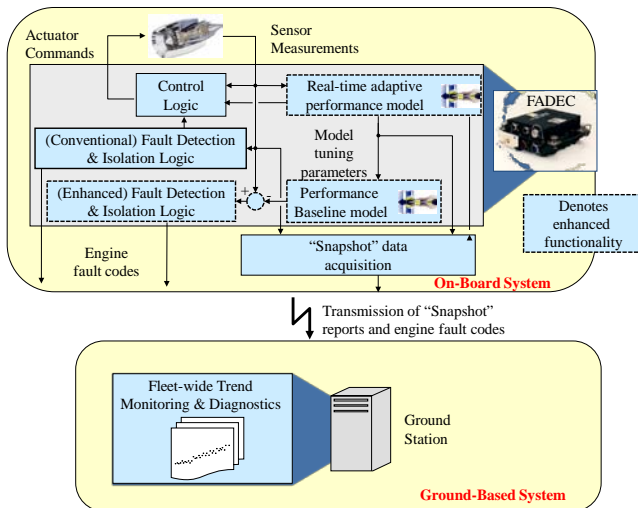


Fig. 4 Proposed enhanced gas path health management architecture.

#### IV. INTEGRATED TESTING AND FUTURE DIRECTIONS

The work described above features the development of advanced sensors and diagnostic capabilities to detect the early indications of faults, which would present a safety hazard to the aircraft and its occupants. A unique aspect of this work is demonstration of these maturing technologies on an operational engine in series of tests called Vehicle Integrated Propulsion Research, or VIPR. VIPR is an approach to health management research that aims to integrate engine testing with on-going diagnostics and sensor system development. This testing is unique in that a high bypass turbofan engine will be purposely modified to test the effectiveness of the health management system to detect these faults. The VIPR series of tests are planned with expanding diagnostic and sensor suite integration over the series of tests. The technologies discussed above are examples of capabilities to be demonstrated during this testing.

Future development for propulsion health management will require advances in both sensor technology and GPHM. In sensor technology, a complete system approach is necessary to revolutionize measurement technology in harsh environment conditions moving towards smart sensor systems [40]: sensors, signal processing, wireless communication, and power. The ability to create complete sensor systems that can be placed wherever needed, like a postage stamp, without the need to rewire the systems (“Lick and Stick” technology) is viable in silicon (Si) based technology for near room temperature operations [41]-[43]. Fig. 5 shows a “Lick and Stick” smart leak detection system using silicon based technology including

signal conditioning, data storage, power, telemetry, and three sensors in one package. A complete “Lick and Stick” smart sensor system approach allows improved sensor data and improved capability to implement the system. Development is needed to enable smart sensor systems that can operate at high temperatures and in the harsh environment of an engine.

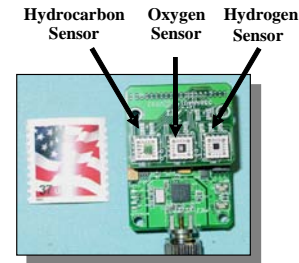


Fig. 5. “Lick and Stick” leak detection system for near-room temperature applications. Configurations of the system include multiple sensors, signal conditioning, power, and telemetry [41].

The GPHM development promises to enable the earlier detection of gas path faults. In addition, the on-board model allows the real-time estimation of unmeasured engine parameters. This could prove to be highly enabling for model-based controls, module performance deterioration tracking, enhanced cockpit displays and annunciations, and usage-based lifing calculations. Future work is planned to quantify the diagnostic benefits provided by the enhanced architecture described in this report. This includes quantifying the reduction in diagnostic latency and the reduction in detectable fault magnitudes offered by the on-board approach.

The integration of both improved sensor technology and engine diagnostics including GPHM is expected to have significant impact on the safety of future aviation systems. It is planned to demonstrate such possible impacts in future on-engine demonstrations that integrate both sensor technology and advanced diagnostics.

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