Overview of Modern Instrumentation Technology Concerning Prognostics and Health Management and Control in Aero Turbine Engines

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ABSTRACT

In recent years new technology for sensor and general instrumentation in turbine engines have graduated towards widespread implementation. Control and prognostics and health management (PHM) of gas turbine engines requires reliable measurement of physical phenomena in the engine that exposes sensors, electronics, and wiring to extreme temperatures. Such environmental conditions have, historically, limited the potential for instrumentation. The phenomena that need to be measured or analyzed include air pressure, mass flow, air flow, fuel flow, temperature, humidity, thrust, fuel composition, frequency response, structural warping, and vibrations. Historical shortcomings in computing power, instrumentation robustness, and wiring access have encouraged conservative control laws that maximize the usage of limited information. Most notably, there is interest in designs that attempt to integrate a notion of distributed or hierarchical control and improve PHM capabilities. New technology can provide instrumentation in previously inaccessible areas, superior computation, and control logic implementation for helping to realize these new systems. Several technologies being considered are fiber optics, wireless systems, and hybrid strategies. Optical fiber data instrumentation uses fiber optic cables that are extremely flexible and thin, agnostic to electromagnetics, and resistant to high-temperature or extreme condition environments. Optical fiber sensors have been shown to withstand temperatures up to 1300 °C. Their flexibility and small size mean they can be threaded through extremely narrow or treacherous areas to provide strain and temperature measurements conducive to "smart skin" sensing within the engine structure. Recent improvements in interrogation technology means fiber optic sensors can be multiplexed hundreds at a time to provide multipoint sensing. The electro-optic interrogator keeps electronics away from high-temperature areas and allows for information to be pooled digitally. High-temperature *electronics allows the deployment of "smart sensors" or chip-enabled instrumentation that can perform data integrity checks and A/D conversion autonomously. These electronics also facilitate wireless data transmission regimes whereby the transmission channel is wireless, and instruments are fully-equipped transceivers. These systems would be lightweight and, with appropriate software support, be well-suited for decentralized control. In addition, new technologies are being developed for wireless data transmission, blade tip clearance measurements, and dynamic pressure measurements. Research indicates the development and implementation of technologies like these will enable the creation of longer lasting, more durable, and more easily maintainable aircraft instrumentation and distributed control systems. This paper elaborates on the new approaches, their technological readiness, their uptake in the industry, and the anticipated promise on both scientific and economic returns for these approaches.*

Key Words: *Sensor, Engine Instrumentation, Turbine engine, Control, EHM/PHM, Ultra High Temperature (UHT), Optical Sensing, High Temperature Electronics (HTE)*

1. INTRODUCTION

In recent years new technology for sensor and general instrumentation in turbine engines have graduated towards widespread implementation. Control and prognostics and health management (PHM) of gas turbine engines requires reliable measurement of physical phenomena in the engine that exposes sensors, electronics, and wiring to extreme temperatures. Such environmental conditions have, historically, limited the potential for instrumentation [1]. The phenomena that need to be measured or analyzed can include air pressure, mass flow, air flow, fuel flow, temperature, humidity, thrust, fuel composition, frequency response, structural warping, and vibrations [1][2][3]. Historical shortcomings in computing power, instrumentation robustness, and wiring access have encouraged conservative control laws that maximize the usage of limited information [1]. The principle methodology of flight control has been known as Fly-By-Wire (FBW). The FBW system uses analogue wiring and a central computer called the Full-Authority Digital Engine Controller (FADEC) to monitor and control sensors and actuators [1]. Although effective, the method has historically been criticized for its high-weight requirements, lack of modifiability, and lack of robustness; meanwhile, industry has focused on lowering lifecycle costs and improving efficiency, therefore encouraging a shift to alternative architectures. Most notably, there is interest in designs that attempt to integrate a notion of distributed or hierarchical control and improve PHM capabilities [4].

New technology can provide instrumentation in previously inaccessible areas, superior computation, and control logic implementation for helping to realize these new systems. Several technologies being considered are fiber optics, wireless systems, and hybrid strategies [4][5]. Fiber optical data instrumentation uses fiber optic cables that are extremely flexible and thin, agnostic to electromagnetics, and resistant to high-temperature or extreme condition environments. Silica Fiber optical sensors have been shown to withstand temperatures up to 1300°C [6]. Their flexibility and small size mean they can be threaded through extremely narrow or treacherous areas to provide strain and temperature measurements conducive to "smart skin" sensing within the engine structure [7]. Recent improvements in interrogation technology means fiber optic sensors can be multiplexed hundreds at a time to provide multipoint sensing. The electro-optic interrogator keeps electronics away from high-temperature areas and allows for information to be pooled digitally [8]. Ethernet interface and instrumentation, appropriately shielded for the environment, allows sensor data, instruments, and data concentrators to be connected to a digital local area network (LAN) infrastructure within the flight control system [9].

High-temperature electronics allows the deployment of "smart sensors" or chip-enabled instrumentation that can perform data integrity checks and A/D conversion autonomously [10]. These electronics also facilitate wireless data transmission regimes whereby the transmission channel is wireless and instruments are fully-equipped transceivers. These systems would be lightweight and, with appropriate software support, be well-suited for decentralized control. Digital structures could provide the architecture of the control law in such systems, overcoming the physically-bound architectures of other methods [4]. Non-intrusive stress measurement systems may be used to sense dangerous vibrations in fan and compressor blades [11]. Thermographic phosphors could potentially be used for detecting temperature on ceramic matrix composites (CMC) and thermal barrier coated (TBC) engine components [12][13][14]. In addition, new technologies are being developed for wireless data transmission, blade tip clearance measurements, and dynamic pressure measurements. Research indicates the development and implementation of technologies like these will enable the creation of longer lasting, more durable, and more easily maintainable aircraft instrumentation and distributed control systems. This paper will elaborate on the new approaches, their technological readiness, their uptake in the industry, and the anticipated promise on both scientific and economic returns for these approaches. Special consideration is given to fiber optic instrumentation technology for integrated distributed control of engines.

Prognostic and health management or monitoring (PHM), refers to the process of gathering and analyzing structural component, performance and diagnostic data for system maintenance. As a safety and maintainability-oriented procedure there is the expectation that increased uptake of such systems in future control and instrumentation designs will extend the usable lifetimes of expensive systems providing a reduction in life cycle cost, reduce maintenance costs incurred by unscheduled or non-optimal repair activities, and improve overall engine efficiency by providing increased flight control awareness of engine and aircraft system conditions.

Health monitoring can also facilitate active control in terms of fault-adaptive control designs and provide usage monitoring information to pilots, maintainers and centralized flight control personnel. Performance data can be stored for later analysis allowing development of statistical inference systems for remaining usable life (RUL) estimation and maintenance scheduling [15]. Development of algorithms for analysis of the data and creation of prognostic systems is a separate though equally pertinent consideration.

The development of instrumentation architectures that can support PHM systems requires reliable measurement of physical phenomena in the engine, including: air pressure, mass flow, air flow, air flow fluctuations, fuel flow, gas temperature, structural component temperature, humidity, thrust, fuel composition, exhaust gas composition, component frequency response, component strain level, structural warping, and vibration levels and frequencies. High-temperature electronics utilizing “smart” nodes or fiber optic-based instrumentation systems can deliver these requirements [8][16].

Performance and lifetime of turbine engines are both significantly reduced by uncertainty in various parameters in the hottest parts of the engine, where sensors cannot safely operate. Engines are purposefully run sub-optimally to leave room for surge margins, temperature margins, and other potential sources of error such as fatigue, flow distortion, and deterioration [17][18]. Some engine components can reach temperatures near 1500°C [19]. Health of engine components in these regions is also difficult to directly monitor, where accurate knowledge of the environment is most critical: the lifetime of some turbine components may vary by as much as half with an uncertainty in the operating temperature of only 10°C [18]. Currently, the conditions in the hottest parts of the engine are computed using sensed values from cooler parts of the engine in front of the burner and after the turbines. As increasing performance and efficiency requirements continue to push temperatures up overall, previously used sensors are becoming inadequate even for use near the exhaust [18]. There is a need for sensors and control hardware capable of withstanding higher temperatures to meet performance requirements and extend the lifetime of turbine engines.

This paper considers engine instrumentation technology in the contexts of both controls and engine health management (EHM)/PHM while reviewing their performance characteristics and capabilities.

2. HIGH TEMPERATURE ELECTRONICS

Silicon carbide (SiC) electronic components are the most promising technology to enable high temperature electronics, having many advantages over silicon. SiC components can withstand much higher temperatures than silicon, which is limited to about 150°C [20]. This is because reverse leakage current is proportional to carrier mobility concentration, n_i. which is an exponential function temperature [21]. 6H-SiC has an n_i of about 10^{-5} cm^{-3} at 300K compared to 10^{10} cm^{-3} for bulk Si [20][21]. This allows it to operate at significantly higher temperatures (theoretically in excess of 900°K) without experiencing failure due to reverse leakage current [20]. The lower carrier mobility concentration is a consequence of SiC having a wider bandgap. In addition to its inherently lower reverse current leakage, SiC also has a higher critical electric field, E_C, than silicon. On-state resistance is proportional to the inverse of E_C^3, meaning the resistance of SiC is on the order of 1/1000th that of silicon [22]. Additionally, it has a higher thermal conductivity, allowing it to dissipate heat faster. Some properties of 4H-SiC (the most commonly used polytype [23]) and Si are shown in Table 1.

Table 1: Comparison of properties of Si and SiC

Parameter	Si		4H SiC	
Bandgap [eV]	1.12	[24]	3.2	[24]
Critical Electric Field [V cm^{-1}]	~3×10^5	[25]	~3.3×10^6	[26]
Thermal conductivity [W m^{-1} K^{-1}]	160	[27]	380	[27]
Coefficient of Thermal Expansion [ppm K^{-1}]	3.0	[27]	4.3	[27]
Elastic Constants [GPa]	$C_{11} = 165.6$ $C_{12} = 63.9$ $C_{44} = 79.5$	[28]	$C_{11} = 507\pm6$ $C_{12} = 108\pm8$ $C_{33} = 547\pm6$ $C_{44} = 159\pm7$	[29]

Note that some of the properties of SiC may be considered drawbacks. The higher coefficient of thermal expansion and significantly higher stiffness make SiC difficult to work with over large temperature ranges, as SiC components will stress the materials they are bonded to more than silicon components, potentially causing damage [23][27]. For example, Herold et. al. found that a 9mm2 SiC device produce similar strain loads on the solder joints as a 64mm2 Si device when heated [27].

The most comprehensive resource for SiC literature is [30]. However, significant advances for high temperature and power electronics are made on a yearly basis. Some examples of recent state-of-the-art achievements are given here, with a focus on high temperature electronics. SiC components capable of operating in 500°C environments or higher have been demonstrated for 6H [31][32][33][34][35][36][37], 4H [38][39][40][41][42][43][44][45][46][47], and 3C [51] polytypes. The first successful devices used the 6H polytype [31][32]. NASA Glenn Research Center funded further research that established reliability for 500 hours of operation at 500°C with several improvements to their previously tested logic gates, produced from commercial 6H-SiC epitaxial wafers[33]. Reliability was further improved, and in 2008 and 2009, thousands of hours of successful operation of 6H-SiC JFETs at 500°C were reported [34][35]. However, due to its higher mobility, most recent work has been conducted using the 4H polytype. 4H-SiC devices have been reported to operate at temperatures as high as 961°C [47]. Recent results have also demonstrated comparable reliability of 4H-SiC devices to the previous 6H-SiC devices. In May 2018, Neudeck et. al. presented a 195-transistor 4H-SiC Integrated Circuit (IC) along with three ring oscillator clocks (two others failed) that were operated in a 500°C environment for approximately 10,000 hours (>1.10 years) [46].

Many sensor packages using SiC electronics have also been demonstrated recently at high temperatures, and some examples important to turbine engines are listed here. In 2013, Yang presented a wireless electronics package to go with a Pt-Pb thermocouple was demonstrated at temperatures up to 450°C and centrifugal loads of 1000g [48] as well as a wireless pressure sensing system that operates up to 450°C and uses a commercial piezoresistive MEMS pressure sensor [49]. Later that year, Soong et. al. presented a monolithic 6H-SiC JFET-based transimpedance amplifier that was operated up to 450°C [50]. Marsi et. al. created a 3C-SiC based MEMS packaged capacitive pressure sensor that showed high reliability in temperatures up to 500°C [51]. Scardelletti et. al. demonstrated a capacitive pressure sensor using a Cree SiC MESFET that operates up to pressures of 350 psi and temperatures of up to 500°C [52]. Okojie et. al. demonstrated a 4H-SiC piezoresistive pressure sensor up to 200 psi and 800°C [53].

While many impressive feats have been demonstrated in the laboratory, SiC devices still face significant reliability challenges that prevent off-the-shelf electronics from achieving the same temperatures, stresses, and pressures for prolonged operation. A number of issues have been identified in the use of SiC at lower temperatures (≤200°C) and high voltages/high currents. The users of SiC for high temperature electronics with lower voltages/currents intended for turbomachinery will need to verify that these issues are not a problem in the turbomachinery environment, or explore solutions to alleviate these issues. Micropipe defects used to be a significant issue, but newer manufacturing techniques have significantly lowered their rates of occurrence from ~50-100/cm^2 in 2000 to 0.05/cm^2 by 2014 [54]. Voltage threshold instability and bipolar degradation are two of the biggest problems still affecting SiC devices. Voltage threshold (V_T) instability is the tendency of threshold voltage in SiC devices to shift due to the application of a significant voltage while at a high temperature [23][55][56]. Shifts in V_T for SiC occur in the same direction as the gate-bias voltage; positive bias results in a positive V_T shift, and negative bias results in a negative V_T shift [23][54]. Positive shifts result in efficiency losses, while negative shifts increase drain-leakage current [54]. Recent evaluations of commercial SiC devices produce varying results, but show that while voltage threshold instability is still a concern, improvements are being made. Göthner found significant V_T shifts in 2nd generation Rohm SCT2080KE SiC MOSFETs [23]. Green et. al. experimented with 1st generation (purchased May 2012) and 2nd generation (purchased May-September 2014) devices from two undisclosed vendors [54]. Older devices showed significant drift, but no evidence of negative V_T drift was found in the newest devices for either brand, and positive drift was less than 1V for both when tested at 175°C [54]. A more recent evaluation of DMOSFETs from three vendors (Cree C2M0280120D, Rohm SCT2450KE, and ST Microelectronics SCT20N120), published in 2017, showed hysteresis drift was again less than 1V for all devices tested at 175°C, with tests that ranged from 14-280 hours long [57]. However, it is noted that drift was highly dependent on the temperature, and that the maximum rated operating temperatures for all tested devices is ≤ 200°C [56].

Bipolar degradation is also a significant issue for SiC devices, characterized by increased forward voltage V_F. The cause of the increase in V_F is the growth of Shockley-type stacking faults, which are changes in the polytype of SiC at certain locations [58]. The faults nucleate around imperfections in the crystal called basal plane dislocations [58][59]. However, low basal plane defect manufacturing techniques have been developed [58][59], and newer commercial devices do not show signs of bipolar degradation [64].

3. SENSORS

One of the most important areas of sensing in a turbine engine is the vibration of compressor and turbine blades. It has been reported by some sources that over 40% of turbine engine failures are due to blade vibrations and High Cycle Fatigue (HCF) [60][61], while others report only 24% are due to HCF [62]. However, in either case HCF was the biggest single cause of failure in turbine engines in the 1990s [62][63]. Turbine and compressor blades are carefully designed to avoid resonant frequencies that may be encountered during operation, so HCF from flawed designs are rare [65]. However, Foreign Object Damage (FOD) can cause small imbalances or modify airflow, leading to vibrations [65], and at the same time, provide a source of initial damage from which cracks may grow.

From a PHM perspective, the ability to monitor vibrations is very valuable, as it can assist in diagnosis of damage and prognosis of failure from fatigue. Historically, vibrations were monitored by a combination of strain gauges, slip rings, and radio telemetry units [66]. Physically planting devices on compressor/turbine blades disrupts airflow and can cause undesirable effects [67][68]. The most common method of monitoring blade vibration in recent literature is Blade Tip Timing (BTT), also called Non-intrusive Stress Measurement Systems (NSMS), but these techniques have been studied and used for many decades. Szczepanik et. al. present an informative timeline of development of NSMS technologies [69]. In a NSMS, the time between each pass of a particular location of the blade tip (like the leading edge) across a measurement device in the engine case is precisely measured. Variations in the arrival times (compared to the arrival time expected based on the shaft speed) give information about blade vibrations, which are used to detect issues like flutter, stall, and blade damage [71]. This method, as its name suggests, does not interfere with the operation of the blades and sensors housed in the casing do not have to endure as harsh of an environment, allowing them to last longer.

Since NSMSs are fixed in the stationary casing, the frequencies they can measure are limited by the number of sensors and the rotational velocity of the turbines/compressors. For a number M of evenly spaced sensors, the relationship describing the maximum measurable frequency ω_{max}, as a function of the rotation speed Ω is $\omega_{max} = \Omega M/2$ based on Nyquist sampling theory [67]. However, methods for reconstructing more sparsely sampled frequencies with fewer sensors have been proposed [72][73][74][75].

Some examples of techniques used by NSMSs include the use of capacitance [76], inductance [69][70], microwave sensors [78], eddy currents [79][80], optical sensors [81][82], and blade wakes [83] to measure vibrations. Some of these systems are capable of simultaneously measuring tip clearance in addition to tip timing [69][77][78][84].

a) FBG temperature and strain sensors

This section focuses on reviewing the modern capabilities of fiber optic sensing in the context of new instrumentation models. Fiber Bragg grating (FBG) sensors have the most promising capabilities and offer a potential for non-intrusive sensing of temperature, pressure, and mechanical strain. This technology, more advanced in recent years, allows the development of instrumentation architectures that can exploit the collection of new types of measurement data for health monitoring and advanced modern controls. Whereas in the past, sampling speed and processing requirements made such systems unviable, optical interrogator technology is now capable of supporting hundreds of FBG sensors per fiber at processing rates in MHz compared to hundreds of kHz previously available. FBGs have now been established as a precise, high-resolution, reliable, and extremophile solution to the problems of dynamic and static strain measurement as well as temperature and pressure measurement within the very hot gas path of the gas turbine engine [8].

FBGs are created by physically inscribing a pattern into the structure of the fiber optic. The pattern creates a reflective volume that filters wavelengths of transient photons, the parameters of the filter being characteristic of the grating. This wavelength-selective filter reflects a narrow band of wavelengths centered on the grating's characteristic wavelength, referred to as the Bragg wavelength, λ_B. The Bragg wavelength is related to the grating pitch, λ, and the mean refractive index of the core, n, by $\lambda_B = 2\lambda_n$. The fiber refractive index and the grating pitch will vary when strain is applied to the FBG or the temperature is changed. These attributes serve the basis of a sensing regime [8].

Mihailov et al showed that optical fiber sensors can fare well in cryogenic and high-temperature environs typically encountered for aerospace, nuclear, and geothermal applications. This resilience depends on the coating and packaging used for the fiber sensors and the type of fiber used. For instance, whereas silica fibers can withstand temperatures to 1190 °C before softening occurs, sapphire fibers can withstand as much as 2040 °C. Typically sapphire fibers are limited by their cost and the difficulty in adding claddings to long lengths of sapphire fiber. Nevertheless, pure silica fibers can withstand temperatures as much as 1800 °C. Copper and gold-nickel coatings allow fiber sensors to withstand temperatures as much as 1083 °C (in the case of copper) to 1455 °C (in the case of nickel-under-gold), which is much higher than standard acrylate coatings provide. “Tubings” are useful as temperature sensors, and include Inconel and stainless-steel types with maximum temperatures from 1372 to 1480 °C. Fibers can then be attached by epoxy, ceramic adhesives, or soldering for a plethora of high-temperature attachment options [7][85]. This slate of temperature capabilities makes fiber sensors ideal for the gas path environment.

Temperature sensing probes using fiber Bragg grating sensors have been demonstrated by Tregay. A probe concept model involves an optical fiber thread connected to an interrogator with three high-temperature FBGs separated by 20 mm each (center-to-center). The gratings together constitute a multiplexed sensor. Temperature dependence of the FBG is assumed to be somewhat nonlinear and dependent on the method used to manufacture the FBG, hence they must be calibrated. These probes can however be safely mounted in the exhaust path as they can withstand the high temperatures in that environment.

Fiber lines can be produced with diameters no greater than the width of a human hair, and can maintain a signal without signal degradation and without noise for several kilometres [8]. These lines are also highly flexible; they can be strung throughout very narrow passages within the structure of the airframe itself, allowing for the possibility of structural health monitoring via the measurement of stresses and strains [86]. Grattan and Sun describe three approaches to the deployment of SHM based on optical sensing: individual single-point sensors, distributed sensing across the entire optical fiber, and quasi-distributed sensing across a number of single-point sensors [87][88][89][90]. Of these the quasi-distributed method can be used for sensing in large structures. Garcia et al did research on measuring strain in a helicopter tail boom with a distributed elongation sensor, and strain in a steel plate using a single-point long period grating [86]. They identified a clear capability for optical sensing-based SHM with FBGs the most promising bet as long as two issues could be resolved: the deliberate decision by members of industry to pursue uptake of this technology and the development of certification standards for aircraft structural SHM.

In order to retrieve the sensors' measurements, the use of an optical interrogator is required. The interrogator feeds an input signal to the fiber and reads the wavelength of the reflected light. The discrepancy between the input and reflected signals can be interpreted to determine the physical measurements taken by the sensors. The optical interrogator can measure changes in the wavelength with sub-picometer resolution, thus allowing sub-microstrain resolution sensing**.** The optical interrogator uses a routing and interface module (RIM) to attach an unspecified length of fiber with an unspecified maximum number of FBGs to a photonic spectral processing (PSP) subsystem. The responsibility of the interrogator in this regard is to process the spectral data through the optoelectronic interface to store measurement data digitally. The fiber thread could potentially be kilometers long, and threaded through very narrow or sharply-winding passageways that other instrumentation channels would struggle to access. Continually, the interrogator fires a laser into the fiber, through each grating, and analyzes the reflected spectra to calculate changes in the Bragg characteristics of each grating.

For integration in the engine, a “smart” interrogator may be desirable, which can allow it to store measurement data digitally, process the signal electronically, and communicate with other interrogators and with the cockpit. The smart interrogator is a microcontroller combined with an electro-optic interface. The local control unit acts as a local computer (responsible primarily for calculating the electro-optic interface), while the monitor unit reports data to the superior control entities via a digital communication network, which may be wireless or wired depending on needs and capability. The physical or wired component of the digital bus would deliberately avoid extreme instrumentation areas, as the fiber bus allows.

b) Thermographic phosphors for CMC and TBC engine components

Thermographic Phosphors have shown significant potential for determining the surface temperature on Ceramic Matrix Composites (CMC) and Thermal Barrier Coated (TBC) components [91][92][93][94]. The ability to make temperature measurements on TBC coated components is especially important since TBCs allow gas turbine components to survive higher temperatures in the hot section of engines, while having acceptable life times. Because of the high levels of reflected radiation associated with TBCs, Pyrometry is prone to extremely high error levels, and is unable to scan over the surface of a component which severely limits the surface area which it can be used to make measurements on. Thermographic Phosphors are rare earth doped ceramic substances which fluoresce, or emit light, when exposed to ultra-violet light. Because they are ceramic substances, they adhere very well to both CMCs and TBCs. Certain characteristics of the emitted light change with temperature, including brightness, color, and fluorescence duration. The latter is most commonly used for temperature measurement. The basic components needed to make this type of measurement consist of an excitation source to excite the phosphor to fluoresce, an optical probe that provides for illumination of the coating and collection of the fluorescence, the coating and the method for applying it, a data acquisition system, and a data analysis protocol. Typically, a short duration LED or laser source is used as the excitation source to illuminate the phosphor coating which in turn luminesces visibly in distinct lines of fluorescence. When the illuminating source ceases, the luminescence will persist for a characteristic time, steadily decreasing. The time required for the brightness to decrease to 1/e of its original value is known as the decay time or lifetime. Decay time measurements are made by exciting the phosphor with a pulse of ultraviolet radiation and measuring the decay time of one of the lines of fluorescence through a narrow band filter to eliminate as much of the background radiation as possible. The decay time method of making temperature measurements has been successfully used in a variety of structural measurement applications. An attempt to make temperature measurements on a first stage turbine vane yielded marginal results, indicating the need for additional development prior to its capability to be successfully used in the environment of a turbine engine.

A second, less commonly used method of temperature detection is based on intensity ratios of two separate lines of emission; the change in coating temperature is reflected by the change of the phosphorescence spectrum. This method enables surface temperature distributions to be measured. In addition to making surface measurements, the intensity ratio method has the advantage that polluted optics have little effect on the measurement as it compares ratios between emission lines. The disadvantage of this method is that it is a much more complicated test method to incorporate into gas turbine engines.

While the previously mentioned methods are focused on temperature detection, the inclusion of phosphorescent materials into the physical structure of the TBC, especially if done in a layered fashion where different dopants are located in varied depths of the TBC, can essentially make the entire surface of the TBC a sensor. This "full surface TBC sensor" would have the ability to detect a variety of parameters, such as heat flux, TBC erosion, spallation, or other aging mechanisms or damage which the TBC may be experiencing.

c) Sensors for velocity gradients and shear stresses

In the recent past, the determination of velocity gradients has relied almost exclusively on the use of hot wire anemometry to measure the instantaneous velocity at different locations of the gas flow being monitored. Hot wire anemometry measurement relies on the *convective* heat loss to the surrounding fluid from an electrically heated sensing wire or element.

The measurement of velocity fluctuations in a flow requires a sensor, in this case a wire, which has a time response of sufficiently high frequency. The time constant of even very thin wires are limited and the response amplitude of these wires at higher frequencies decreases with increasing frequency. For these reasons, some type of compensation must be made to the wire output. Earlier approaches used a constant current anemometer with a compensating amplifier that had an increase in gain as the frequency increased. In theory, the output from the wire can be compensated to infinite frequencies. However, as the frequency increases, the noise output from the compensating amplifier will eventually equal and ultimately exceed the wire output, which limits the gain that can be obtained.

Unfortunately, hot-wire anemometry has limitations which reduce its resolution in space, time, and amplitude. Much of the data of interest which has been obtained using hot-wire anemometry has been limited to small perturbations. Problems have been identified in some applications where larger levels of fluctuation occur. High level fluctuations have been shown to influence the mean voltage measured across the heated wire. Because of this, it is important to calibrate probes in flows with lower levels of fluctuations. Additionally, due to the mass associated with the wire supports, there can be significant heat loss from the wire due to conduction to the relatively cold supports. This heat loss results in a temperature distribution along the length of the wire which, in turn, causes a variation of heat transfer from the wire along its length. In order to compare the rate of heat transfer from one wire or probe with another, the heat transfer rates must be corrected for these heat losses. The spatial resolution of a wire is limited by the length of the wire and the size of the smallest scales of fluctuations in the flow. Wire proximity to walls of wind tunnels or to other surfaces can introduce measurement errors due to increased heat transfer from the wire as a result of conduction to the relatively cold walls or surfaces. The spatial resolution of multi-wire probes is further limited by the distance between the wires. Also, hot-wire probe intrusion into the flow can cause severe disturbance in certain flows.

Shear-stress sensors are usually classified by measurement method into two distinct groups, direct or indirect techniques. A sensor using the direct measurement technique will directly measure the shear force acting on the surface of interest. This is usually achieved by the utilization of a "floating element" balance. Indirect measurement techniques require a theoretical or empirical correlation, which is typically valid only for very specific conditions, to correlate the measured property to the wall shear stress. The Micro Electro Mechanical Systems (MEMS) community has developed a variety of different indirect transduction sensing methods using a variety of techniques such as micro-optical systems to measure near-wall velocity gradients, hot-film sensors, and mechanical micro-fences.

d) High temperature thermocouples

The long and widespread use of thermocouples has made them the predominant method of making temperature measurements in many areas, including turbine engines. A thermocouples is an electrical device made up of two dissimilar electrical conductors or wires joined at one end to create a junction where the temperature is measured. These electrical junctions produce a temperature-dependent voltage as a result of the thermoelectric effect. This voltage can be used to determine temperature.

New control systems for advanced technology engines require very fast response times. Thermocouples must be able to respond in fractions of a second versus seconds. Transient temperatures, material melting points and indications of surge must be sensed immediately, since the faster the response time the more time the digital control system will have to react and correct any undesirable condition and potentially prevent complete engine failure and the potential loss of an aircraft.

Type S thermocouples are typically the high temperature thermocouple used in turbine engine testing today. The two electrical conductors that make up the type S thermocouples are 90%Pt-10%Rh and 100%Pt. Type S thermocouples are rated to have a maximum temperature capability of 1600°C which is adequate to monitor structural temperatures in the hot section of current military turbine engines. Unfortunately, these thermocouples experience many of the same problems which plague contacting sensors. These sensors must be affixed to the surface of the engine component being evaluated and the high temperature erosive environment in the hot section of a modern turbine engine can be extremely challenging to the survival of almost any contacting sensor. Delamination from the component surface as well as erosion of the electrical junctions of the thermocouple are major failure issues of the sensor itself, while lead wire failure is another failure mechanism which will cause the complete loss of thermocouple data.

While significant advances have been made in recent years that have improved hot section sensor survivability, significant problems still exist which reduce the useful lives of sensors in this environment. Additional development efforts are needed to provide hot section sensors which are survivable enough to meet the needs of the PHM community.

e) PHM Sensors

Sensors are essential part of the PHM systems. To have an efficient PHM system, the important characteristics of the sensors such as the sensitivity of the detected signal, their location in the system, and whether these sensors should be wired or be wireless, should be considered. Sensors are to be selected depending on the range of the parameter to be measured, their precision, and their capacity to function in specific environmental conditions (such as hot or cold sections of the engine).

The last decade has seen increased research in the development of new sensors whose primary role is in the support of PHM. Some of these applications include oil debris monitors (ODM), oil condition monitors (OCM), gas path debris monitoring systems for ingestion (IDMS) and exhaust (EDMS), blade health (ECS), blade tip timing and tip clearance, high frequency accelerometers and acoustic sensors, exhaust emission sensors, and the like [2].

4. COCLUSIONS

In this paper we surveyed the benefits of PHM as an enabling discipline consisting of technologies and methods to assess the reliability of a product in its actual life cycle conditions to determine the advent of failure and mitigate system risks. The survey of literature on EHM/PHM indicates that the engine gas-path performance monitoring research represents the majority of EHM related research. The paper contains the basis of gas turbine monitoring integrated with controls provided an overview of the available solutions for diagnostic problems.

Algorithm approached to solve EHM problem are traditionally handled at FADEC or PHM box is going to be handled differently when the distributed controls/PHM system is implemented. All prognostics and EHM will be treated locally in a hierarchical manner. And each sub-system has to be smart enough to identify the issues before going through up the chain of command, and because the success of all subsequent diagnostic stages of fault detection, fault identification, and prognostics strongly depends on deviation quality. To enhance the quality, the cases of abnormal sensor data should be examined, and error sources should be identified at the local level.

The cost of reactive maintenance has become prohibitive, especially for complex and integrated systems. Even with the development of comprehensive standards focusing on interoperability and reuse, the way systems are maintained must and is changing rapidly. System providers are required to implement interoperable systems /sub-system based on the available standards. With the recent focus on CBM and prognostics, the need exists for exchanging more robust information in a timely manner that will enable identifying and correcting a fault before it occurs. As with traditional testing, standards for CBM and PHM are also required. Propulsion digital enterprise will possibly revolutionizes dealing with maintenance and controls integration. Optical fiber lines will be playing an important role in future instrumentation as they can be produced with diameters no greater than the width of a human hair and can maintain a signal without signal degradation and immune to electromagnetic interference (EMI) for several kilometres.

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