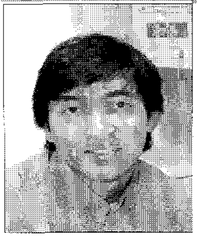
High Temperature Sensors for Propulsion Systems



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1. Introduction

State of the art for harsh environment high temperature sensors has improved considerably for the past few years [1-14]. Existing fatigue and life prediction studies for high temperature zones (1000C-1400C) in propulsion systems depend on strain/stress values computed from indirect measurements of temperature, flow velocity, pressure, et al. Thermomechanical Fatigue (TMF) prediction which is a critical element for blade design, is strong function of the temperature and strain profiles. Major uncertainties are from inability of current instrumentation to measure temperature and strain at the critical locations. This would be an enabling technology for blade design optimization at high temperature environment. Ability to measure strains, temperature and pressure accurately in different high temperature zones would deeply enhance the effectiveness of Life Prediction Systems and DARWIN (SWRI's Design Assessment of Reliability with Inspection) type programs for regime spectrums and damage prediction and assessment.

Continuous development of new engines and improvements to existing engines requires that enormous numbers of conventional sensors be installed and their output recorded. Testing and validating new high temperature sensors is necessary before the sensors are installed on jet engines.

2. Life Controls Perspective

From a Controls perspective, it is desirable to know the condition of the entire gas turbine engine with a high degree of accuracy. The Control System attempts to schedule the engine to provide the best performance. Typically this is done by way of closed-loop feedback control, operating the engine to nearly the limits of its capability, preferably using on-board sensor generated data as a means of providing thatfeedback. In the hotter sections of the engine, those feedback measures are inferred, by means as diverse as a simple mathematical relationship between a measured parameter and the feedback of interest; or as complex as an on-board model. Either way, increasing degrees of uncertainty are introduced into feedback parameters that must inferred from other sensed inputs to the control. This results in the need for the introduction of both steady-state and dynamic "back-offs," which are built into the control to ensure that limits continue to be observed even with the use of inferred feedbacks. The effect of these back-offs reduces overall performance of the engine. Direct measurements of hot section parameters will enable the magnitude and number of those back-offs to be reduced, thereby allowing engine performance to closer approach optimal.

Similarly from a Diagnostics/Prognostics standpoint, precise knowledge of engine condition is highly desirable. The purpose of Diagnostics is to assess current enginecondition, whereas Prognostics trends these assessments over time to predict future condition. The goal is to reduce the uncertainty of the current condition assessments to a minimum, since inaccuracies will have an integrally significant impact on projections of future condition over time. As for Controls, direct measures of engine condition, such as would be possible using high temperature sensors in the hot section of the engine, would provide the best basis for projection of future condition. Through Diagnostics and Prognostics, it is possible to detect changes in engine performance that are precursors to problems (even failures) well before they occur, most desirably, in time to allow engine maintenance to be scheduled to minimize financial impact to the aircraft operator. The earliest indications of degradations leading to failures are usually subtle, often hidden under the uncertainty bands of the sensor measurement. Again, this is compounded for the inferred parameters used in the performance analysis of the engine hot section. Yet, the harsh operating conditions of the engine hot section often leads to incidences of premature degradation. High-temperature sensors capable of making direct hot section observations will significantly increase the span of the "early detection" window.

3. Harsh Environment Sensors and Health Management

Health management has been identified as a key driver in the turnaround time, availability, launch support infrastructure, cost, and reliability of the jet engines. Therefore, confidence in the health management systems is an absolute necessity. To realize an improved health management system, a new generation of extremely reliable and robust sensor technology is required. Sensors will provide information for system safety, life prediction, and on-condition maintenance. The sensors will be placed on test articles and a full characterization of sensor performance in a high temperature and vibration environment will be performed and followed by sensor design and integration improvements and any required subsequent characterization tests that will allow for nominal sensor performance in a harsh environment. This new information, in some cases, may be obtained with other methods, but the sensors themselves may have been influencing the results. For example, conventional strain gages have been shown to damp blade vibrations by comparing strain gaged blade vibrations to non-strain gaged blade vibrations measured using a noninterference stress measurement system

Testing activities encompass a combination of bench tests and rig tests, each providing realistic environments. The tests to be done are described below. Realistic test environments are necessary for determining the suitability of the sensor for long-term use as a health management sensor. Special procedures need to be developed for successful deployment of each of these proposed technologies and the best way to develop these steps is though realistic tests. Mounting and integration issues will be worked so that the sensors can operate in the harsh environments of the engine.

4. Some Issues Related to High Temperature Sensor Technologies Validation

There is a range of success criteria for a high temperature sensor test. It usually starts with, "did it survive" and goes to, "does it accurately represent the directional strain or measure accurate surface temperature in the part". The first question is usually answered by looking for an open or short circuit indication. The latter question requires knowledge about the expected strain field. In the flat plate test, the coupling of the thermal field and the stress field greatly adds to the complexity. Since the flame test also has a severe chemical environment, there are considerable benefits associated with running the blister test at the flame test stands. For the thermo-mechanical fatigue testing, this rig would have a combined thermal and mechanical effect. Again, this test would only be a pass/fail type test. If the sensor is mounted at the substrate-coating interface, there may have significant issues to overcome regarding lead routing and insulation. In this case the proposed program would consider applying the sensor to the cold side of the specimen.

For accuracy, drift or degradation of the sensor, de-coupling of the stress and thermal fields becomes necessary. A single cycle, quasi static test on an MTS machine would be run where the control conditions are isothermal and load controlled, being careful not to constrain the tensile specimen during the warm-up. The specimen has to be load controlled out of concern for creep.

When tensile fatigue testing is performed, the min/max stress ratio won't go below r = .05 due to grip issues. For fully reversed bending (r = -1) testing, a beam bending specimen would be used. Care must be taken to not induce significant thermal gradients and stresses due to heat flow into the grip. Some of the bend test rig may be more susceptible to this issue as compared to the tensile test. In either case, at least one specimen wouldbe tested with temperature measurements just outside of the gage section to understand the temperature gradient. Attachment of the temperature and strain sensors would be carefully considered for the fatigue testing since it may induce premature failure in the specimen. Samples with and without sensors would be tested to determine the effect. Specimen failure is irrelevant as long as the strain is known and the strain gage is still accurately indicating and accumulating load cycles.

Material, test temperature, and strain range selection must not be made independently. Maximum usage temperature limits may be chosen for metallurgical reasons pertaining to phase change, re-crystallization, or formation of precipitates. Higher temperature capable nickel alloys often exhibit creep at low stresses and elevated temperatures. Lower temperature nickel alloys may have a higher creep resistance, but will naturally be operating at lower temperature. The application for these sensors would be considered with the same material and heat treat condition would be used for testing. Then similar operating temperature and stresses would be replicated in the test specimen

5. Required Specifications for a Sensing technology applicable to High Temperature Zones in a Propulsion System

1 Survivalibility at extremely high temperature conditions (Fig 1).

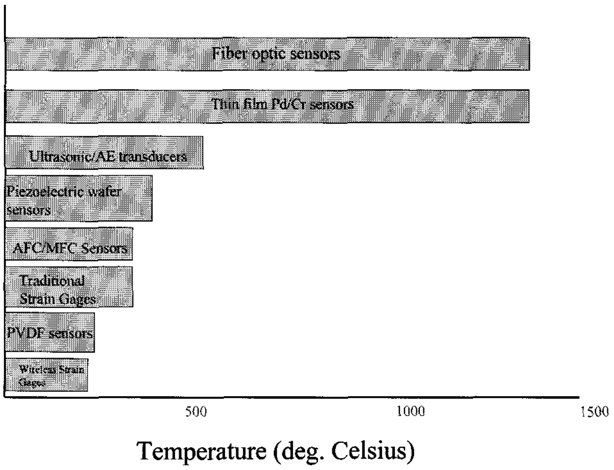

Figure 1 Operating Temperature ranges for various types of Sensors

2 Long term sensor durability, stability and drift in presence of thermomechanical fatigue cycles (TMF). Durability means that sensor remains attached and functional.

3 Adequate sensitivity at high temperature zones.

4 Maintaining adequate adhesive bonding to the structural substrate during the life of the sensor. Preventing otherwise delamination/disbonding of the sensor.

5 Data Acquisition/Hardware availability, especially portions of the DAQ units connected to the sensor to receive output needs to survive high temperature. Hardware attachments are significant source of problems associated with high temperature.

6 Not prone to EMI (electromagnetic interference) and extreme temperature changes.

6. Emerging Sensing Technologies

6.1 Thin-film Thermocouples

For measurement of surface temperature, commonly available thermocouples use four types of base metals, namely: K-chromel/alumel (-320F to +1500F), E- Chromel/Constantan (-320F to 1650F), T-Copper/Constantan (-320F to 700F), and J Iron/Constantan (-320 to 1380) [1]. However NASA GRC is currently developing ceramic based thin film temperature measurement sensors. Thesesensors will be installed on turbine blades under a TBC and will provide structural and thermal characteristics of the blades during operation. This information is critical to predicting turbine blade life. These gages eliminate structural integrity problems associated with the installation of conventional thermocouples. The thin film material used is CrSi2/TaC. The thermocouple details and the performances of the Chromium Silicates with respect to Platinum thin films can be found in the ref [2].

6.2 Multifunctional Sensor

This multifunctional sensor developed by NASA GRC [9-11] provides several types of information, such as part strain and direction of strain, flow velocity and direction, heat flux, and surface temperature. These sensors are non-intrusivebecause they are flush mounted or welded with the surface of engine components and have an installed thickness less than 0.001 in. Current efforts are on development of Indium Tin Oxides ceramics to be used instead of Pd/Cr [3] for the sensor material.

6.3 High-Temperature Thin-Film Instrument Attachments for Data Acquisition

This instrumentation would be used on advanced, high-temperature capable materials that are not compatible with conventional instrumentation, i.e., they may react or their bonds degrade at high temperatures. Thin-film instrumentation also aids in making accurate measurements on advanced materials, because their minimal mass has no adverse impact on performance, coatings can be chosen for high-temperature compatibility, and molecular bonds are less likely to fail [10]. Silicon Carbide will be investigated for high temperature attachment electronics. The existing attachment for GRC sensors are that the sensors are first attached to the Platinum (Pt) wires deposited on the ceramics. These electrodes are attached to a Pt pad at the end of the ceramic and are connected to Pt wires. The wires are then mounted on slip rings for transmission of data from the rotating frame to the stationary structure. It is extremely important to make sure that the hardware attachments of the sensing technology for the data acquisition survive the harsh environment.

6.4 Fiber Optic Sensors

Normally Extrinsic Fabry-Perot inferometry is used to develop these high temperature fiber optic sensors. To measure both strain and temperature, a broadband light source is transmitted to the cleaved end of a single-mode fiber. To perform the strain measurements, upon reaching the end of the fiber, the light is partially reflected while the remaining light travels past the end of the fiber and is reflected off a secondary reflector. The reflectors (also fibers) are aligned with the main fiber in a capillary tube and attached to a substrate. The two reflected light signals interfere with each other forming a fringe pattern. As the substrate strains, the distance between the two fiber end-faces vary, causing the fringe pattern to change. Using a spectrometer, the changing gap is measured to obtain the strain. The sensor is less prone to failure because the fiber itself is not being strained by the substrate. The temperature sensor has a small, single-crystal chip on the end of the fiber. The two faces of the chip are reflectors. Precise temperature can be obtained by measuring the temperature-dependent optical path length through the chip. Different types of fibers are used for making the FO sensors. For temperature less than 700 C: Silica Fibers are used for FO sensor. For temperature greater than 900 C currently single crystal Sapphire fibers are being investigated. The advantages of the Sapphire fibers Versatile in terms of multifunctionality, can measure temperature, pressure, strain. The disadvantages are sensor construction is difficult because of large modal volume of sapphire fibers. New FO sensor materials being developed: in this area include Photonic Crystal Fibers and Wholly Fibers. Competitive Assessment for High Temperature FO Sensors developers include industrial development from Luna Innovation, Prime Photonics, Smart Fiber, Blue Road, Cidra, HHT, federal Labs include NASA Langley, NASA Glenn, Sandia National Lab, Naval Research Lab and Universities include Virginia Tech, Stanford University, and Georgia Tech.

6.5 Magnetostrictive Sensors

This sensing approach is based on a novel thin-film magnetostrictive sensor material that has recently been developed by SwRI for turbine engine applications (14). SwRI is testing this wireless sensor on stator vanes upto 600F. This thin-film is 4 micron thick and achieves high activation efficiency, as well as temperature stability, using alternate crystalline and amorphous nano-layers. Defect detection is accomplished by activating the magnetostrictive thin-film causing emission of ultrasonic guided waves into the component that are subsequently backscattered and detected by the same sensor in "pitch-catch"fashion mostly done in a pulse echo mode. Energy harvesting and radio frequency (RF) communication enable multiple, individually addressable sensors to detect and monitor damage in structural airframe components. This sensing system provides a low mass sensing system, which does not affect the dynamic response of the component and high efficiency sensor in power density requirements for electromechanical conversion. The robustness, durability and the accuracy level of the magnetostrictive sensors needs to be tested in flight and high temperature environment. This sensor has a potential to survive uptp 700-800C.

7. Proposed High Temperature Sensor Technologies Testing

The following tests for assessing the sensor durability, survivability, stability and drift are to be considered for sensing technologies evaluation. Initial work would involve choice of sensor structural substrate material, sensor mounting and integration methods. It must be noted that choice of the structural substrate material for mounting of the sensors and testing under very harsh environment is very important to avoid creep related issues affecting the tests. Different sensor mounting and integration techniques would be explored like etching and then diffusion bonding and flush mounting the sensors onto the structural substrate or by molecularly bonding the sensor element on a structural ceramic layer like alumina and depositing directly onto the structure. The sensor and the sensor attachments would becontinuously monitored delamination, wrinkles, cracking or layer peeling off under exposure to extreme environment. The connectivity in the hot zone of the sensor to the data acquistion system would also be monitored closely. The following paragraphs discusses in details some of the harsh environment tests that would be conducted on the sensor.

7.1 High Temperature Environment Testing

High temperature environment testing would involve the following tests: 1) Isothermal static tests, 2) Bi-Axial Tensile Torsion Test 3) Thermomechanical Fatigue Test, and 4) Blister Test. TMF testing lends itself well to quantifiably being able to assess the high temperature sensor under varying thermal and mechanical strain fatigue conditions. The test system is capable ofengine relevant cycle shapes and in-phase and out-of-phase thermal and strain cycling as well as mission specific cycle shapes. This specimen is used with al turbine alloy coating systems as well as uncoated material evaluations. The high temperature sensor would be assessed for it's crack detection capability, durability under fatigue conditions, accuracy, bonding ability with plasma coating systems, temperature measurement ability and strain measurement capability with the test. The TMF testing is conducted in a furnace with 2300F capability, which is attached to a 20 KIP servo-hydraulic load frame capable of frequencies up to 20 Hz at small displacements to simulate low and high cycle thermo-mechanical fatigue. For the static and TMF tests, this 20 KIP load frame is used. The isothermal static tests (tensile-torsion) at high temperature on the dog bone specimens with sensor mounted can also be conducted for sensor and sensor attachment durability, drift and stability characterization. The tensile-torsion test is conducted in an MTS biaxial load frame in a furnace with 2300F capability. The tests are controlled using MTS 458 controllers and data acquisition will be performed using LabView software to monitor the sensors and the output from the tests.

7.2 Blister Testing

Blister testing uses propane and oxygen to create high radial thermal & strain gradients in a flat circular plate (termed "Hot Spot Blister Testing"). The test is used in combustor panel assessments. Cooling air is provided on the cool sideto further enhance the desired thermal gradient. High temperature sensors are tested under extreme thermal gradient conditions using this test by positioning it across the test plate.

7.3 Vibration Test

Vibratory tests that are normally done on engine components to ascertain the durability of the sensors and the sensor attachments under various engine vibratory conditions. The accelerometers are mounted on an engine component undergoing vibratory tests for a force sweep test by using an electrodynamic shaker.

8. Conclusions

Presently there exists no way for direct measurement of strain at high temperature in engine components such as combustion chamber, exhaust nozzle, propellant lines and turbine blades and shaft. Existing fatigue and life prediction studies for high temperature zones in propulsion systems depend on strain/stress values computed from indirect measurements of temperature, flow velocity, pressure, et al. Thermomechanical fatigue (TMF) prediction, which is a critical element for blade design, is a strong function of the temperature and strain profiles. Major uncertainties arise from the inability of current instrumentation to measure temperature and strain at the critical locations. This prevents the structural designer from optimizing the blade design high temperature environment, which is a significant challenging problem in engine design. Ability to measure directly strains in different high temperature zones would deeply enhance the effectiveness of aircraft propulsion systems for fatigue damage assessment and life prediction. State of the art for harsh environment high temperature sensors has improved considerably for the past few years. This article laid down specifications for high temperature sensors and did the technological assessment of these new sensing technologies. This article presenteda review of the recent advances made in harsh environment sensing systems and takes a peek at the future of such technologies. The following conclusions are made from the above discussions:

1. The propulsion system can be divided into several temperature zones and appropriate sensing technologies can be deployed in the different zones.
2. Motivation, required specifications and application for high temperature Sensing systems have stated.
3. Sensor Characterization and durability test under harsh conditions defined.
4. High Temperature Multifunctional Sensors available (TRL3-TRL 5) with variable temperature ranges.
5. Wireless/networking applicability very much essential.
6. Needs to characterize the sensors and develop/modify the attachments as required.
7. Further continued sensor development and maturation strategies required for OEM deployment in instrumented engines.

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