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14. ABSTRACT

The accurate measurement of gas flow conditions in the compressor, combustors, and turbines of gas turbine engines is important in order to assess performance, predict failure, and facilitate data-driven maintenance. Surface and point measurements of pressure and temperature in the high temperature regions of the turbine help engineers optimize performance, improve fuel mixing and burning in the combustor, and to redesign compressor and turbine stages based on actual measurements. There currently exists no sensor technology capable of making pressure measurements in the critical hot regions of gas turbine engines. Luna Innovations is developing extremely high-temperature fiber optic pressure sensors based on inert refractory ceramic construction. During the project, several breakthroughs have been achieved in high-temperature fiber optic packaging, sensor design, and high-speed measurement. In-engine testing is scheduled to begin in mid August at Virginia Tech. Additional testing will be conducted with a major aircraft turbine engine manufacturer. By the conclusion of this project, Luna Innovations will have produced a fiber optic pressure sensor capable of making measurements at up to 14000C, 750psi, at a sample rate of 1.0MHz.

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HIGH-TEMPERATURE, HIGH-BANDWIDTH FIBER OPTIC PRESSURE AND TEMPERATURE SENSORS FOR GAS TURBINE APPLICATIONS

F49620-03-C-0010

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Abstract

The accurate measurement of gas flow conditions in the compressor, combustors, and turbines of gas turbine engines is important in order to assess performance, predict failure, and facilitate data-driven maintenance. Surface and point measurements of pressure and temperature in the high temperature regions of the turbine help engineers optimize performance, improve fuel mixing and burning in the combustor, and to redesign compressor and turbine stages based on actual measurements. There currently exists no sensor technology capable of making pressure measurements in the critical hot regions of gas turbine engines. Luna Innovations is developing extremely high-temperature fiber optic pressure sensors based on inert refractory ceramic construction. During this project, several breakthroughs have been achieved in high-temperature fiber optic packaging, sensor design, and high-speed measurement. In-engine testing is scheduled to begin in mid-august at Virginia Tech. Additional testing will be conducted with a major aircraft turbine engine manufacturer. By the conclusion of this project, Luna Innovations will have produced a fiber optic pressure sensor capable of making measurements at up to 1400°C, 750psi, at a sample rate of 1.0MHz.

Objective

The overall objective of this program is to produce a prototype temperature compensated pressure sensors that will operate up to 1400°C gas temperature. A summary of the target sensor parameters identified are listed in Table 1.

To meet these requirements, Luna will leverage its considerable experience with ceramic sensor construction to accomplish the following objectives:

Objective 1: Produce prototype temperature compensated pressure sensors.
Objective 2: Continue development on high-frequency fiber optic sensor readout systems
Objective 3: Conduct laboratory and field testing at realistic test facilities.
Objective 4: Develop detailed strategy for commercialization

Three key advancements for the Phase II research include: 1.) passive temperature compensation using novel transducer construction, 2.) active temperature compensation through co-located temperature sensors, and 3.) development of a high-speed optical readout system.

Table 1. Target performance parameters for high-temperature pressure sensor.

Sensor	Desired Parameters	Phase I Demonstrations	Phase II Goals
Pressure	1,400 °C (2,550 °F) 0-750 psig, FS, +/- 1%	1600°C in air 0.9% for 750psig FS	Temp. compensation 1500psi burst at temp.
Temperature	1,600 °C (2,910 °F) +/-25°C (+/-45°F)	Survivability of materials to 1600°C	Operation in long-term turbine tests. +/-2°C (+/-3.6°F)
Electronics	Frequency: ~150 kHz, Output: 0 – 5 V Analog	Frequency: 1.0MHz Digital output	Compact design 0-5V analog output

The capability of sensor operation at these elevated temperatures will allow engineers to locate sensors at engine stations not currently feasible with conventional sensors. For both test instrumentation and engine control sensors, this technology leap will afford turbine designers with reliable test and control data that until now has been completely unavailable.

Approach

The approach taken involves the combining optical fiber sensor technology with inert refractory ceramic pressure sensor probe construction. Fiber optic sensors do not rely on piezoelectric material properties and will, therefore, function at extremely high temperatures. Inert ceramics such as alumina and sapphire are used for the hot zone components to resist oxidation and chemical attack.

Progress to date

The key technical challenge of hermetically packaging an optical fiber into an all-ceramic pressure sensor probe at high temperatures has been overcome. On a related project, pressure probes were produced and tested at up to 800°C, gas temperature, and 500psi. This accomplishment represented a breakthrough in the state of the art for high-temperature pressure sensors. This project has focused on overcoming the considerable challenge of combining all of the requirements listed on To meet **these requirements, Luna will leverage its considerable experience with ceramic sensor construction to accomplish the following objectives:**

Objective 1: Produce prototype temperature compensated pressure sensors.
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Three key advancements for the Phase II research include: 1.) passive temperature compensation using novel transducer construction, 2.) active temperature compensation through co-located temperature sensors, and 3.) development of a high-speed optical readout system.

Table 1 into a single sensor. Much progress has been made in the readout system development, passive and active temperature compensation, high-temperature (>800°C) packaging, and high-speed electronics/software development.

Readout system development

The HyperScan system uses two lasers at wavelengths of 1541.4 and 1546.1nm to generate two optical signals that are 90degrees out phase with each other, called quadrature, for an air gap of approximately 62.5μm. The sample rate is adjustable from 5,000 to 1Million samples/second (8 selections). Software was developed for post processing the data captured from the sensors. The software is designed to process data from a data from a comma separated value (*.csv) text file. The software allows processing the data with or without a calibration file. A calibration file is necessary if the data captured during the measurement does not contain a full interference fringe. Use of the calibration file allows the absolute pressure as well as the dynamic pressure to be resolved. The calibration file must be generated from a data set captured while the sensor is manipulated to move through a full fringe. Additional development will streamline the software to make it more robust and easier to use for applications outside of the laboratory.

The HyperScan system is, to our knowledge, the fastest fiber optic sensor readout system in existence. The high sampling rate allows for dynamic analysis of turbulent and unsteady flows in the vicinity of turbine blade tips.

Remote interrogation

The initial sensor design incorporated remote interrogation of an Extrinsic Fabry-Perot Interferometer (EFPI) cavity. A basic diagram is shown in Figure 1. This design allowed the transducer to reside in the hot zone while the more sensitive optics remained in a cooler region and therefore required no external cooling. Significant difficulties were encountered in trying to couple this approach with the dual wavelength HyperScan system described above. The key difficulty was due to the long coherence length of the lasers used in the system. This produced interference patterns not only within the EFPI cavity, but also between all of the other surfaces in the collimator structure including both lens surfaces, both window surfaces, etc. These multiple reflections could not be resolved using the dual wavelength system and the collimated approach was, therefore, replaced with an actively-cooled sensor approach.

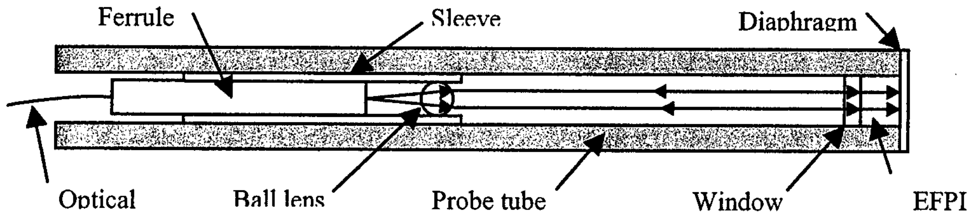

Figure 1. Basic diagram of a remotely-interrogated EFPI-based sensor.

Every effort was made to keep the remotely-interrogated approach by eliminating the extraneous reflections. Anti-reflective coatings were considered but were rejected due to the extreme high-temperatures required. A lens with an angle polished back face was used, as opposed to a spherical ball lens to eliminate the reflection between the fiber and the lens, however even the low amplitude reflection that remained significantly interfered with the signal processing. Flat surfaces were buffed to produce a more diffuse reflection. However, transmission through the resulting diffractive surface was minimal and prevented interrogation of the EFPI cavity. Various lens materials and shapes were also investigated and failed. Ultimately it was concluded that combining the HyperScan system with the remote interrogation approach was, at best, extremely impractical. It was then decided to accomplish similar results by using an air-cooled sensor approach.

Sensor design

The current sensor design consists of a sapphire diaphragm with a fiber bonded inside of a fiber optic ferrule. The ferrule is bonded inside of a stainless steel housing with a sintered metal seal. The diaphragm is mounted to the probe using a high-temperature ceramic braze. Cooling ports are provided to allow active air cooling. The operational temperature is limited by the sintered metal bond which has a maximum usable temperature of approximately 900°C. A basic drawing of the current design is shown in Figure 2.

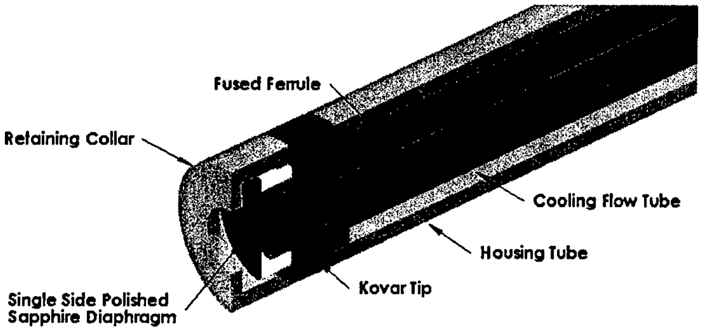

Figure 2. Basic diagram of current pressure sensor design.

Tests were performed to determine the amount of cooling available. Pressure probes were inserted into a furnace and cooling flow applied. Numerous variables were evaluated including cooling port size, pressure applied, cooling port geometry, etc. An example of one test is shown in Figure 3. The thermocouple measurement is taken outside of the probe. The sensing chamber measurement is taken internal to the probe in the vicinity of the sintered metal bond.

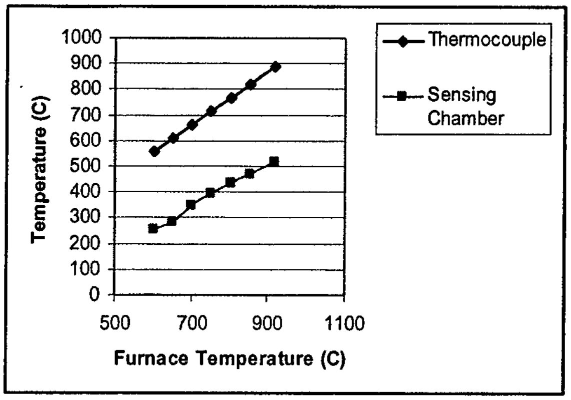

Figure 3. Cooled probe testing. Active cooling gave a 400°C temperature reduction.

Temperature compensation is another key issue which is directly tied to obtaining high-precision absolute pressure measurements. The initial design included sapphire components oriented along two different axes. Under isothermal conditions, the expansion of the two components would cancel each other thus eliminating the zero offset. A number of challenges arose, however, that made this approach impractical. First, the bonding required to produce the part was to be accomplished by an outside vendor who ultimately reported that the assembly would be a very high risk and would cost >$1,500 per part. Secondly, this approach produced interfering multiple reflections which were discussed above. Third, this form of temperature compensation only accounted for the zero offset but did not account for the temperature-dependence of the Young's modulus of the diaphragm material. Finally, the temperature gradient within the sensor will impart a zero offset which would require extensive modeling to account for. Every effort was made to retain the principle of minimizing the zero offset through CTE and geometry tailoring. The current design accomplishes the same goal using dissimilar materials in construction.

Modeling has shown that utilizing available machining tolerances in sensor construction will still result in undesirable temperature dependence due to the thermal gradients through the sensor. The result would be a low-frequency apparent pressure offset thereby reducing the absolute character of the sensor. For this reason, a secondary pressure probe will be located outside of the hot zone and will measure static pressure only. The two signals will be combined to give both high-frequency and low-frequency data. The fully temperature-compensated probe design is shown in Figure 4. This probe is much larger than initially envisioned and can be reduced in size with additional development. Every effort has been made to solve the extreme challenges of addressing the other required performance goals and, therefore, size was allowed to increase.

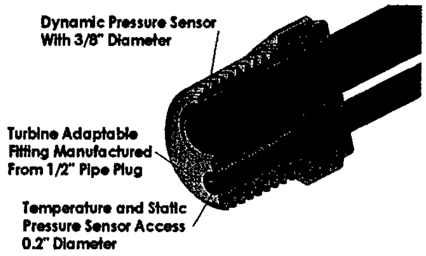

Figure 4. Fully temperature-compensated probe design.

Material selection and packaging

Throughout the entire project, great care has been given to material selection. Materials used in the hot zone include sapphire and alumina. Moving back from the hot zone, Ni-plated Kovar is used as a transition piece between the alumina probe tip and Inconel housing. An alternate material, PM2000, is also being evaluated due to its excellent corrosion resistance without the need for coating. PM2000 forms an adherent aluminum oxide layer. The bulk of the probe housing will be constructed of Inconel which has acceptable corrosion resistance.

Turbine and combustion tube testing

Turbine testing at Virginia Tech in the JT-15D is on-going. Initial tests have been conducted to determine the temperature and static pressure downstream of the first stage blades. Additional testing will be conducted when prototype fiber optic probes are completed. These tests are planned for mid-August 2004. Additionally, testing is being set up with a turbine engine manufacturer to provide a more extreme environment.

Related work

During a Phase II SBIR project recently completed with NASA Dryden, pressure sensors were constructed that were demonstrated to operate up to 800°C and 500psi. This accomplishment was a breakthrough in the state-of-the-art in high-temperature pressure measurement.

During an Army Phase II SBIR currently under way, small size, high-speed temperature sensors have been produced with a sub-millisecond response time and a maximum transient temperature of 1400°C.

Future Work

Future work on this project will include laboratory and field testing of prototype sensors and design work to minimize the size of the pressure probes.

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References
None

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New Discoveries
Disclosures will be filed once prototype is reduced to practice.