Flight Demonstration of Fiber Optic Sensors

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ABSTRACT

Luna Innovations has developed a prototype 8-channel fiber optic sensor system to demonstrate fiber optic sensor operation in flight environments. As an intial flight demonstration, long period grating (LPG) relative humidity sensors along with extrinsic Fabry-Perot interferometric (EFPI) pressure and temperature sensors were installed in an aging Delta 767-300ER jet. The fiber optic signal-conditioning system is a multi-purpose platform that can also be used to operate other types of fiber optic LPG and EFPI sensors, including strain gages, metal-ion corrosion sensors, and fiber Bragg grating (FBG) sensors. The system configuration and operation is described.

KEY WORDS: Fiber optic sensors, Extrinsic Fabry-Perot interferometer, Long period grating, Bragg gratings, Multiplexed sensing, Flight worthy instrumentation, Structural health monitoring

1. INTRODUCTION

To support the use of fiber optic sensors within a flight environment, Luna and Boeing are collaborating to develop and qualify a system, termed the *AEROSCAN*, that will enable interrogation and data collection from numerous optical fiber-based sensors on board civil and military aircraft. The *AEROSCAN* design is leveraged from spectral signal conditioning techniques that Luna has been developing over the past decade to collect real-time data from optical fiber-based sensors. Sensors that can be used with this system include any spectrally interrogated sensor such as: EFPIs, LPGs, and Bragg-based sensors. The current prototype *AEROSCAN* allows interrogation of 8-channels with future channel expansion capable through software upgrades. This system has direct applications in health monitoring of aircraft as well as future applications in biological warfare detection.

2. SYSTEM DESIGN

The presented *AEROSCAN* system is an optical signal processing system that leverages a low powered, light weight data acquisition unit termed the Battery Operated Health Monitoring System (BOHMS) developed by the Boeing Company. The BOHMS provides the hand shaking protocol necessary to turn on the *AEROSCAN*, interrogate the optical fiber sensors, log data, and turn the system off, limiting power demand on the battery. Battery operation was implemented to reduce interference with normal aircraft operation allowing for a more rapid on-board integration and demonstration. The *AEROSCAN* flight system can also be controlled by a PC for factory testing and file loading. The photograph, shown in Figure 1a, illustrates the 8-channel flight qualified *AEROSCAN* system with military grade optical connectors and Figure 1b is a photograph of the *AEROSCAN* integrated with Boeing's BOHMS. In this configuration, the *AEROSCAN* is the slave device that returns responses to the host when communication is triggered. Data from this system can be collected every hour, stored to a memory bank, and down loaded during aircraft servicing.

Figure 1a. Photograph of flight qualified 8-channel *AEROSCAN* optical fiber sensor support system

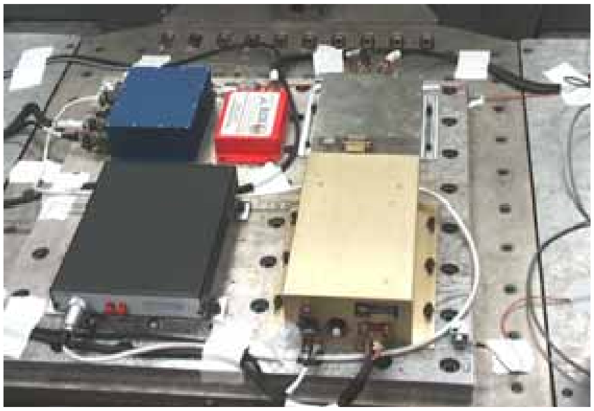

Figure 1b. *AEROSCAN* signal conditioning system integrated with BOHMS.

The BOHMS is an aircraft flight data acquisition system that has been designed to fill a void in commercially available data recorders. Aircraft manufacturers, and military and commercial aircraft users desire a way to monitor such things as high cycle fatigue and corrosive environments, flight loads, bonded joint structural integrity, and repair patch bondline integrity for in-service aircraft. To perform these functions a rugged, small, and lightweight data acquisition unit has been constructed and is currently being further upgraded. Running off of battery, power the system will collect data autonomously independent of any aircraft. This unit is designed to interface with other data acquisition cards and multiple sensor types, to be placed in remote hard to access areas of the aircraft, spacecraft, lunch vehicles, ships, and ground vehicles for monitoring the health of structural components. The system monitors not only the *AEROSCAN* fiber optic channels but also analog sensors. These analog sensors are used side by side with fiber optic sensors to validate the fiber optic sensor readings.

The *AEROSCAN*, a flight qualified optical signal conditioning system, fits in a 5.75” by 10” footprint with a height of 2.75”. All components and mounting accessories total 7.84 lbs of weight and run off battery power. The power consumption during data acquisition is 203 mA at 15 V_{DC}. During sleep mode, the power consumption drops dramatically down to 1-2 mA. Future system developments will focus on lighter, smaller, and higher channel count designs. Figure 2 illustrates the signal-conditioning techniques for interrogating multiple types of optical fiber sensors. System hardware includes multiple broadband sources that inject light into each sensor channel for interrogation. Each sensor provides a reflection back through the coupler tree to the spectrometer for spectral evaluation. This system is currently set up to interrogate LPGs, EFPIs, and Bragg grating sensors. Each of the optical fiber sensors is interrogated by measuring power spectral density and can therefore be demodulated with identical hardware. Data handling techniques and unique algorithms are used to distinguish sensor output and provide converted optical measurements to physical and chemical readouts.

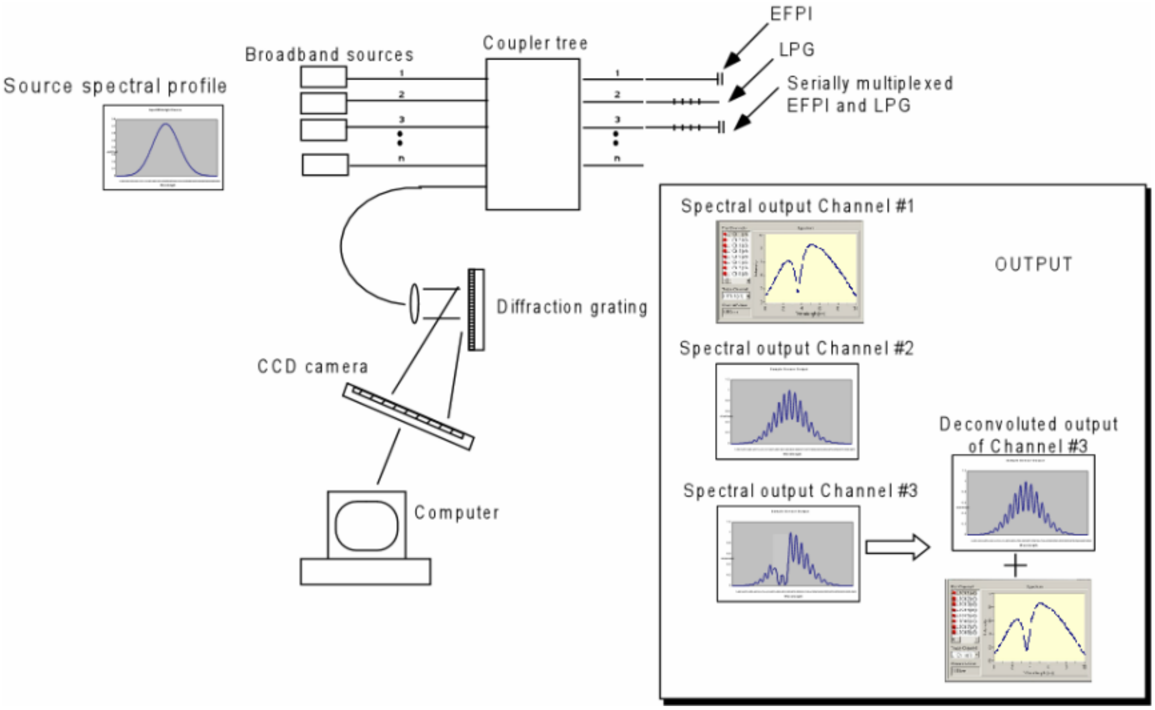

Figure 2. Schematic of *AEROSCAN* signal conditioning concept.

Before delivery to Boeing for evaluation, the *AEROSCAN* was tested in simulated flight environments that included high EMI, extreme cold and heat, and random vibration environments. These environments qualified the unit for installation as a non-primary structure of a commercial aircraft. The results from these qualification tests have proven out the design for flight testing. Figure 3 illustrates the location within the DELTA 767-300ER where the BOHMS system along with demodulation boxes will be installed for flight testing. Future placements will emphasize ease of battery replacement and data downloading.

Figure 3. Location of *AEROSCAN* and BOHMS system within cargo compartment of Delta 767-300ER.

3. OPTICAL FIBER SENSORS

The presented flight worthy health monitoring system is designed to interrogate any optical fiber sensor that is based on spectral-conditioning within the 800 nm range. For demonstration, Luna, Boeing, and Delta installed two LPG-based relative humidity sensors, two EFPI-based temperature and two EFPI-based pressure sensors. Sensing methodologies for the EFPI and LPG-based sensors are described. The proposed device enables the operator to monitor the entire structure for real-time measurements by leaving the sensors connected to the signal conditioning system, or leaving the sensors embedded in the structure and interrogate sensors at time-based intervals to determine the structure health status. The sensors have the advantage of being highly responsive, low profile, and can be parallel multiplexed in large numbers.

LPG-Based Chemical Sensors

The optical fiber long-period grating (LPG) sensor filters light at different optical wavelength, as the index of refraction around the fiber changes, thus creating a loss band as determined by the sensor environment. Refractive index measurements are easily achieved by tracking the wavelength of the spectral shift and correlating to refractive index. A schematic of the LPG sensing platform is shown in Figure 4a with the spectral response to refractive index changes shown in Figure 4b.

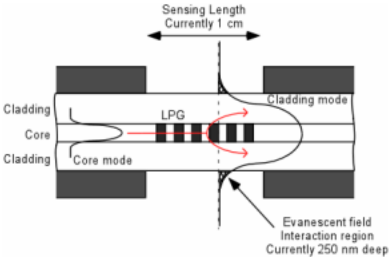

Figure 4a. Schematic of a long-period grating sensor.

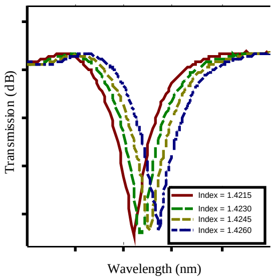

Figure 4b. Shift in wavelength of light coupled out of the LPG w/ changes in refractive index.

LPGs are formed by exposing a germanosilicate fiber to a spatially periodic intensity pattern generated from a high-power ultraviolet (UV) source[1]. Germanosilicate fiber is photosensitive such that optical fiber exposure to certain wavelengths of light, particularly 244 nm, will cause the refractive index of the glass to increase slightly[2]. The spectral location of the loss band due to this modal coupling is a function of the difference in the effective indices of the guided mode and the corresponding cladding mode. The coupling wavelength, λ, for a specific loss band, is given by the expression,

$$\lambda = (n_g - n_{cl})\Lambda$$

where Λ is the grating period and n_g and n_{cl} are the effective indices of the guided and cladding modes, respectively. Variations in the values of Λ, n_g and n_{cl} will shift the position of the coupled wavelength. However, as Λ is a constant parameter of the optical fiber and n_g is essentially independent of the external environment, measurable wavelength change is due entirely to n_{cl} (refractive index surrounding the optical fiber grating)[1]. By coating the sensing surface with films that change refractive index based on target capture, the LPG can be used for chemical and biological sensing [3, 4, 5].

LPG-Based RH Sensing

For this demonstration, humidity sensors were fabricated by immobilizing a hydrophilic polymer, polyethylenimine (PEI), on the surface of a LPG optical fiber. In this configuration, a polyethyleneimine (PEI) layer on a LPG sensing area interacts with the atmospheric water vapor by hydrogen bonding, which results in reversible swelling of the polymer, and consequently, in changing the thickness and density of the polymer layer. As a result, the wavelength shift is observed due to the change of the effective refractive index of the polymer layer[6]. LPG humidity sensors offer high sensitivity, rapid response, good reversibility and repeatability, and high durability. Figure 5 illustrates a typical response of the LPG for various relative humidity measurements. As shown in Figure 6, the LPG-based humidity sensor demonstrates reversible measurements for the whole range of humidity detection. An important advantage in using the LPG-based relative humidity sensor over other alternative analog sensors is that LPG sensors continue to perform after they reach a relative humidity greater than 95%.

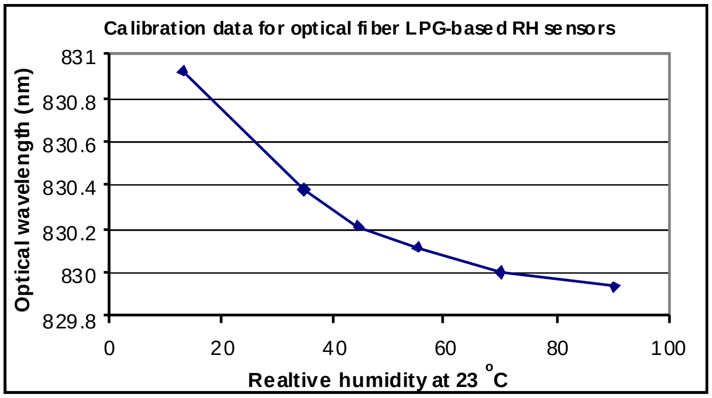

Figure 5. Typical calibration data for optical fiber LPG-based RH sensor.

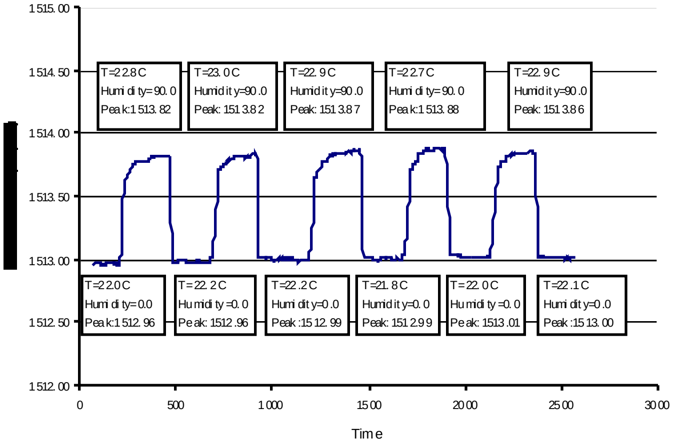

Figure 6. Reversibility data for LPG-based RH sensor between 0.0 and 90.0% [6].

For this flight demonstration, the presented LPG-based RH sensors were co-located next to EFPI-based temperature sensors during installation. Temperature measurements will be used to compensate RH measurement during data analysis.

EFPI-Based Sensing

EFPI sensors use a path difference measurement technique based on the formation of a low-finesse Fabry-Perot cavity between the cleaved endface of a fiber and a reflective surface, shown schematically in Figure 7. Light is passed through the fiber, where a portion of the light is reflected off the fiber/air interface (R1). The remaining light propagates through the air gap between the fiber and the reflective surface and is reflected back into the fiber (R2). These two light waves interfere constructively or destructively based on the path length difference traversed by each. The resulting light signal then travels back through the fiber to a detector where the signal is demodulated to produce a distance measurement. Several different demodulation methods exist to convert the return signal into a distance measurement[7]. This design is typically used as a displacement or strain sensor, but modified designs have been used for temperature[8], pressure[9], skin friction[9], acceleration[10], and refractive index measurements[11].

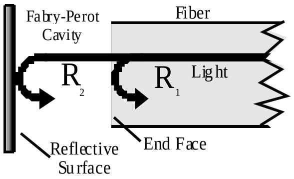

Figure 7. Optical fiber-based EFPI sensing approach used for various sensing applications.

Temperature Measurements

For temperature sensing, a silicon chip is placed on the end of the optical fiber producing two optical paths that interfere according to the path difference. The optical path length through the silicon chip is given by the physical length times the refractive index of the chip, with the refractive index being dependent on the temperature and thickness. Therefore, temperature measurements are made by tracking the change in optical path length of the silicon chip[8]. Figure 8 illustrates a schematic and photograph of the EFPI-based temperature probe and Figure 9 illustrates a typical calibration curve for the sensor.

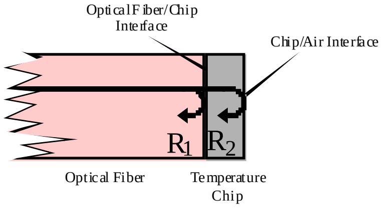

Figure 8a. Schematic and photograph of the fiber optic temperature probe.

Figure 8b. Schematic and photograph of the fiber optic temperature probe.

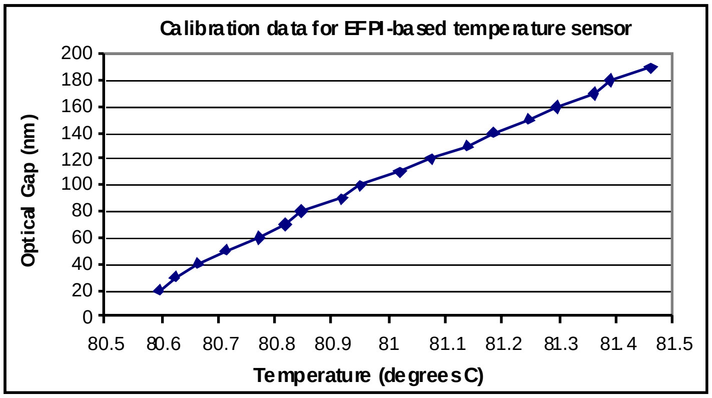

Figure 9. Typical calibration data for optical fiber EFPI-based temperature sensor.

Pressure Measurements

The EFPI-based pressure sensor design consists of a micromachined structure produced on an ultrasonically machined Pyrex base wafer and a silicon wafer that creates the Fabry-Perot cavity. Figure 10 illustrates a schematic and photograph of a typical optical fiber pressure sensor. The optical fiber is 125 um in diameter and the diaphragm is approximately 3 mm x 3mm and 500 microns thick. The optical gap between the bottom of the diaphram and the endface of the fiber creates the Fabry-Perot cavity. This optical gap varies as the diaphragm is deflected, which in turn varies with applied pressure[10]. Figure 11 illustrates a typical calibration data for the pressure sensor.

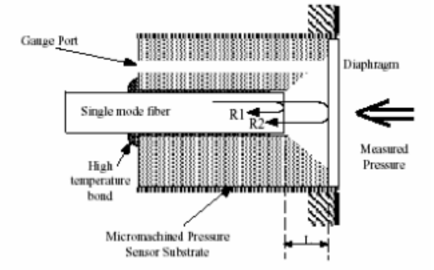

Figure 10a. Schematic and photograph of the fiber optic pressure probe.

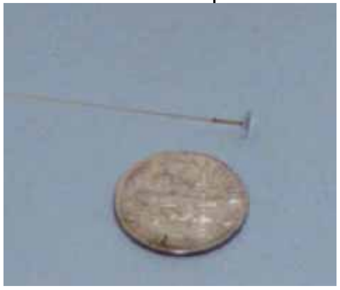

Figure 10b. Schematic and photograph of the fiber optic pressure probe.

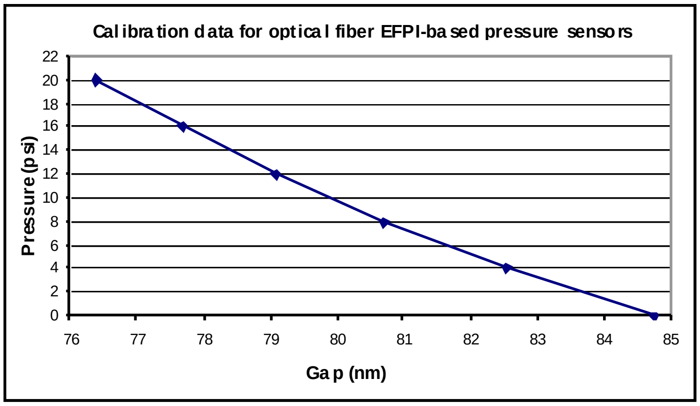

Figure 11. Typical calibration data for optical fiber EFPI-based pressure sensor.

1. SENSOR INSTALLATION

As an initial flight demonstration, Luna, Boeing, and Delta representatives installed the indicated sensor types on an aging Delta 767-300ER jet that has been in service for 12 years and was in the hanger for its 2nd Heavy Maintenance Visit. The objective of this demonstration was to determine installation procedures, proof of concept, data collection procedures, and survivability. Figure 12 and 13 illustrates installation locations near the station (STA) 434 stringer splices connecting Section 41 and Section 43 in the forward cargo bay compartment in the cargo sub floor. This area was selected due to its close proximity to a mounting location near a sidewall compartment that can easily be accessed during servicing. During future testing, sensors will be installed in strategic locations where water is more likely to pool and cause corrosion such as locations within floor beams and under lavatories and galleys.

Figure 12. Bay with insulation and ductwork after sensor installation (taped orange X is where several sensors are located)

Figure 13a. Pressure sensors located between 434 and 456.

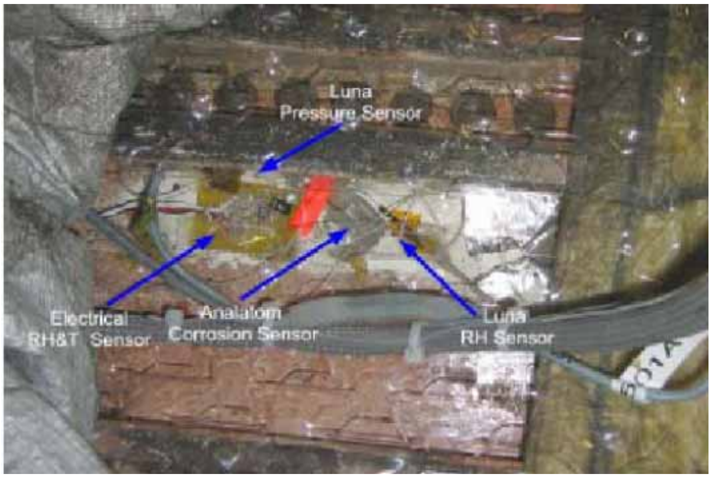

Figure 13b. Final sensor installation between station 412 and 434.

Table 1. Installation location for fiber optic sensors

STA	STA	STR	Position	Sensor Description
434	456	N/A	Cargo Sidewall	Luna F/O Demodulation Box
434	456	35L	Skin, Above Stringer	F/O Temperature Sensor
390	412	35R	On Top of Stringer	F/O Temperature Sensor
412	434	37L	Skin, Above Stringer	F/O Pressure Sensor
434	456	27R	Skin, Above Stringer	F/O RH Sensor
390	412	35R	On Top of Stringer	F/O RH Sensor
434	456	35L	Inside Stringer	F/O Pressure Sensor

Notation: The station (STA) shown for the installation locations in the two left columns form the bay in which the sensors were installed. In the third column, "Above" or "On Top" indicates the outboard direction for the stringer. The sensors were installed near the stringer. As noted, all sensors are located in the forward cargo bay compartment in the cargo sub floor. The sensors are placed at or near the STA 434 stinger splices that connect Section 41 to Section 43.

Discussions with DELTA representatives and the process of installing sensors during this demonstration has provided valuable feedback for not only sensor placement, but future sensor designs and packaging that will enable service personnel to easily handle and route optical-fiber sensors within strategic areas for health monitoring.

4. CONCLUSIONS

This paper presents recent advances in an optical fiber-based flight-worthy health monitoring system. This system supports interrogation of LPG, Bragg, and EFPI- based sensors for health monitoring applications. As an initial flight demonstration, Luna, Boeing, and Delta representatives installed optical fiber-based temperature, pressure, and relative humidity sensors within a testbed to determine installation procedures, proof of concept, data collection procedures, and survivability. This flight test is scheduled for 2003 and will prove out survivability of the system. Future installations and testing will focus on sensor placement within strategic monitoring locations and advanced methods of sensor installation and data downloading. The goal is to provide sensors and data acquisition systems that are easily installed and routed through strategic monitoring locations. Future development on the data acquisition system will focus on expanding the number and type of sensors that can be supported, reducing size and weight, increasing battery life, and providing data downloading procedures that take less than an hour. Sensor development work will focus on increasing the variety of measurement parameters. Researchers are currently expanding measurement capabilities to pH, skin friction, acceleration, and strain sensors that will integrate into the sensor suite for flight worthy health monitoring applications.

5. ACKNOWLEDGEMENTS

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