

Universal Interrogator Approach to Optical Sensors for Aircraft Applications

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Abstract

Recently, there has been an increasing interest in Fiber Optic Sensors (FOS) for aircraft applications. Many of the FOS are based on different transducer mechanisms and hence, employ sensor-specific readout systems. However, for ease of maintenance and cost saving purposes, a 'universal interrogator' that can be used with at least a large sub-group of sensors is the preferred option for deployment in aircraft.

Oxsensis has been developing sensors for harsh environments with focus on land based gas-turbine monitoring and combustion control and more recently is also looking at applying its technology to other areas such as Aerospace and Oil & Gas. In this paper we report on recent progress on the development of a number of FOS and how these could find application in aircraft with a 'universal interrogator' concept in mind.

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Introduction

Recently, there has been an increasing interest in Fiber Optic Sensors (FOS) for aircraft applications. Drivers are general advantages that FOS offer, but that are particularly relevant to aircraft, including weight savings by replacing electrical cables with optical cables, passive and therefore intrinsically safe sensor heads, immunity to Electromagnetic Interference (EMI) and the ability to carry out measurements in a harsh environment. In addition, the increasing use of composite materials results in heightened lightning protection requirements. The desire to move towards More Electric Aircraft (MEA) or All Electrical Aircraft (AEA) could require the deployment of additional sensors, making weight saving even more important [1, 2, 3]. Further, new opportunities arise in the area of Structural Health Monitoring (SHM) due to ease of multiplexing FOS employing Fiber Bragg Gratings (FBG) and the potential to combine operational load monitoring with impact damage detection [4].

FOS often employ sensor-specific readout systems to suit a particular transducer mechanism. However, for ease of maintenance and cost saving purposes, a 'universal interrogator' that can be used with at least a large sub-group of sensors is the preferred option for deployment in aircraft. Oxsensis has been developing sensors for harsh environments, focusing on land based gas-turbine monitoring and combustion control. More recently, we are also looking at applying our technology to other areas such as Aerospace and Oil & Gas. In this paper we report

on recent progress on the development of a number of FOS and how these could find application in aircraft with the 'universal interrogator' concept in mind.

Dynamic Pressure Sensor

Oxsensis dynamic pressure sensor system was originally developed for condition monitoring of land based gas turbines in power generators. A typical requirement would be to measure sub-mbar dynamic pressure variations at frequencies up to 10 kHz on top of a large and slowly varying base pressure, ranging between 3 and 60 bar. The tip of the sensor is in direct contact with the hot gas and tip temperatures may reach 1000°C. The main sensor body is mounted in the engine wall and normally experiences lower temperatures, typically less than 750°C. The design of the sensor head takes advantage of this naturally occurring temperature gradient, enabling it to survive 1000° at the tip. At the back of the sensor the maximum temperature is mainly limited by the optical fiber lead-out and available coatings. Some applications have also asked for simultaneous measurement of temperature. This facility is included in the enhanced pressure sensor. A picture of a pressure sensor head is shown in [Figure 1](#).

There appear to be opportunities for such type of sensor to be deployed in modern aircraft engines. Engine Health Monitoring (EHM) is increasingly used to reduce maintenance costs by analyzing multiple independent signatures and using data trending to detect developing performance insufficiencies and

take appropriate action to mitigate service disruption. For instance, Rolls-Royce Trent 900 engine which powers about two thirds of the Airbus A380 is permanently fitted with about 25 sensors, including pressure, temperature and shaft speed sensors [5]. EHM can also be useful in detecting unusual engine conditions such as engine surge or exceeding limits for turbine gas temperature during takeoff.



Figure 1. Picture of pressure sensor head

Pressure Transducer Mechanism

Fiber optic pressure sensors are most commonly based on measuring the deflection of a diaphragm that responds to pressure, a schematic of which is shown in Figure 2. The diaphragm is held in place by the base and in the centre, is separated from the base by a gap d_1 . The response of the diaphragm to applied pressure is a function of the material properties of the diaphragm and its geometrical dimensions. For an accurate theoretical analysis a Finite Element Method is required, however, for deflections much less than the diaphragm thickness an approximate linear relationship between deflection y and applied pressure p holds [6]:

$$y = \frac{3(1-\nu^2)R^4}{16Et^3} p, \quad (1)$$

where R denotes the diaphragm radius, t is the diaphragm thickness and E and ν are the Young's modulus and Poisson's ratio of the diaphragm material, respectively. From Eq. (1) it can be seen that for a given diaphragm material, both thickness and radius are key design parameters. Both parameters can be used in the design so that for the pressure range of interest a certain maximum value of deflection is not exceeded. For its harsh environment sensors, Oxsensis is employing a monolithic sapphire transducer element. Sapphire offers a number of key properties that make it the material of choice for harsh environments, including high mechanical strength and stability, a high melting temperature above 2000°C, exceptional thermal shock properties, high anti-

corrosion and high anti-abrasion properties, high thermal conductivity and excellent optical transmission over a wide wavelength range [7]. Pressure measurement capability is established by optically measuring the gap ($d_1 - y$).

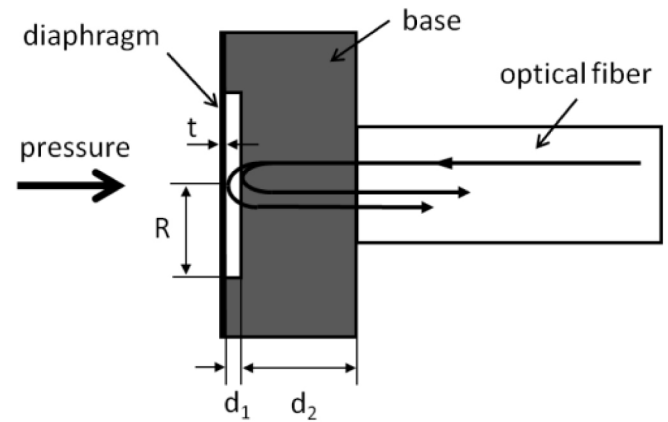


Figure 2. Schematic of pressure sensor head

Dual Wavelength Interrogator

From an optical point of view, the interfaces between air and sapphire present in the transducer element form semi-transparent mirrors with a reflection coefficient of about 7% due to the step-change of refractive index from 1.0 in air to 1.75 in sapphire. As a result, the two interfaces that make up the gap d_1 form a Fabry-Perot (FP) cavity. Illuminating the transducer element by a light source via, for instance, an optical fiber splits the incoming light beam at the first interface. A first return beam is formed from the reflection at this interface. The transmitted part is subsequently reflected at the second interface, forming a second return beam. In comparison to the first beam, the second beam travels an additional distance of $2d_1$, leading to a phase shift ϕ between both beams:

$$\phi = \frac{4\pi n d_1}{\lambda}, \quad (2)$$

where λ is the vacuum wavelength of the light and n is the refractive index of the medium between the two mirrors. If directed to a photodiode, both beams interact and produce an interference fringe. Depending on the value of the phase shift, constructive or destructive interference occurs, leading to a sinusoidal intensity pattern with respect to the gap d_1 . This is schematically shown in Figure 3 for incoming light at two different wavelengths and can be described by the equation below:

$$I = \frac{I_0}{2} [1 - V \cos(\phi)], \quad (3)$$

where I_0 is the intensity of the incoming beam and V is the so-called visibility describing the strength of the interference signal.

By carefully choosing the size of the gap d_1 and limiting the diaphragm deflection to part of the fringe, one can operate in the linear region of a fringe as indicated in Figure 3. In this case, the change in return intensity is a direct measure of the applied pressure. In practice, one simultaneously illuminates the sensor with two light sources of different wavelength and takes the ratio of both intensity curves, outputted as an output voltage V_{PDC} . In this way, possible measurement errors caused by fiber bend losses are minimized as they are common to both intensities [8]. The schematic of the corresponding dual wavelength interrogator (DWI) unit is shown in Figure 4. A distinctive advantage of this interrogation scheme is that it is able to record pressure signals within a large signal bandwidth. Our standard sensor system is designed with a signal bandwidth of 40 kHz as this is the main frequency range of interest for most land based gas-turbine monitoring applications. Depending on application requirements, this can be either decreased to reduce the noise floor or increased for a larger signal bandwidth.

In order to determine the dynamic calibration factor over the whole operational pressure and temperature range a static pressure and temperature measurement is carried out. From that, the dynamic calibration factor is calculated as the slope from the V_{PDC} vs. pressure curves recorded at different temperatures. An example of pressure and temperature calibration data for a sensor designed to be linear up to 3 bara is shown in Figure 5. As can be seen, the pressure response is largely linear and a single calibration factor can be assumed in many practical applications.

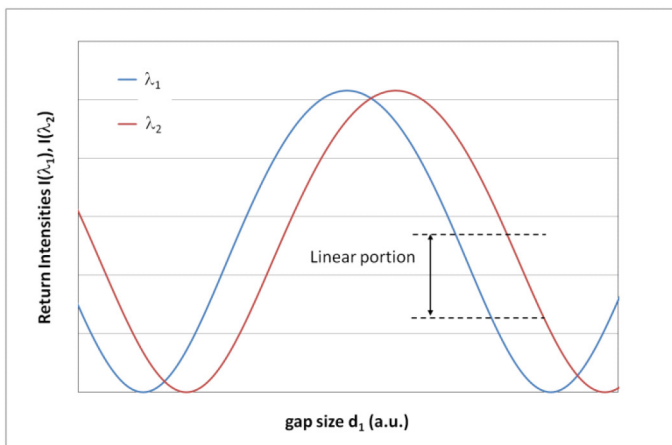


Figure 3. Schematic of interference pattern

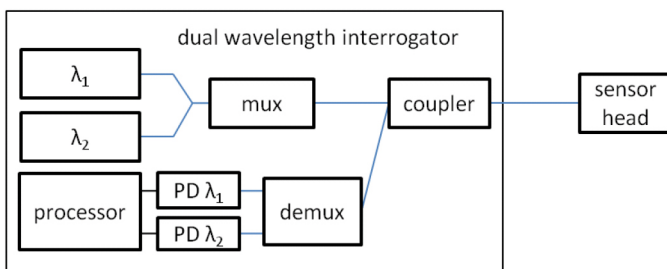


Figure 4. Schematic of dynamic pressure sensor system

Closer inspection reveals the calibration factor varies with temperature, typically by up to $\pm 5\%$ over several hundred $^{\circ}\text{C}$, and that there is also some non-linearity with pressure at a given temperature, typically less than $\pm 10\%$. Whilst this is sufficient for many practical applications in gas turbine monitoring, some applications may require higher accuracy. In addition, the offset between individual calibration curves is a function of temperature, preventing it from being used as an absolute sensor. This has led to the development of an enhanced version where temperature is measured simultaneously at the sensor head, enabling absolute pressure readings and minimizing of calibration errors.

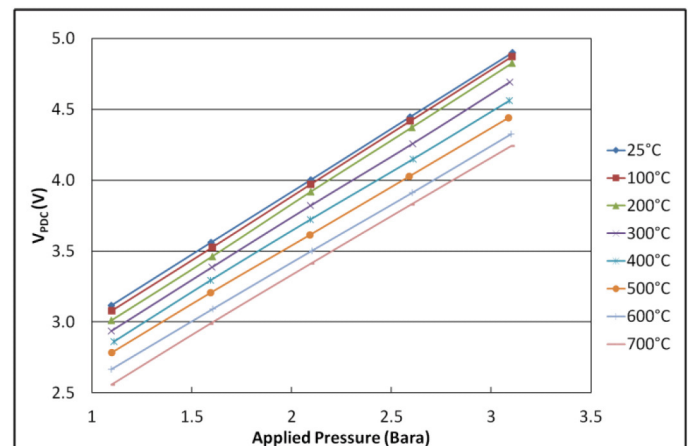


Figure 5. Pressure and Temperature measurement for a 3 bar sensor

Dynamic Pressure Sensor with Enhanced Performance

Temperature Transducer Mechanism

In order to measure temperature at the sensor head, we note that there is a second optical cavity present that is formed by the two interfaces comprising the base. The optical path difference (OPD) or delay between the two reflecting beams equals $2nd_2$, with n being the refractive index of the base material. Both the geometrical thickness d_2 and the refractive index are a function of temperature, and the change in OPD_b with temperature can be expressed as follows:

$$\Delta(OPD_b) = 2d_2 \left(\frac{dn}{dT} + n\alpha \right) \Delta T, \quad (4)$$

where dn/dT is the thermo-optic coefficient and α is the thermal expansion coefficient of the base material, respectively. This cavity is normally not picked up by the DWI interrogator as by design, the OPD of the base is much larger than the so-called coherence length l_{coh} of the light source. On the other hand, the OPD of the pressure sensing cavity $2d_1$ is deliberately made much smaller than the coherence length, enabling the detection of interference fringes as explained in the previous paragraph. Readout of the base cavity is achieved by employing a spectral engine in addition to the DWI unit as