Optical fiber sensor fusion for aerospace systems lifecycle management

Original
Optical fiber sensor fusion for aerospace systems lifecycle management / Aimasso, A.. - 33:(2023), pp. 288-293. (Intervento presentato al convegno 3rd Aerospace PhD-Days 2023, International Congress of PhD Students in Aerospace Science and Engineering tenutosi a Bertinoro nel 16-19 aprile 2023) [10.21741/9781644902677-42].

Availability:
This version is available at: 11583/2983951 since: 2023-11-20T08:05:57Z

Publisher:
Material Research Forum

Published
DOI:10.21741/9781644902677-42

Optical fiber sensor fusion for aerospace systems lifecycle management

Alessandro Aimasso [1,a]

[1]Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Turin, Italy

[a]alessandro.aimasso@polito.it

Keywords: optical fiber, Fiber Bragg Gratings, sensors, systems, aerospace, prognostics and diagnostics

Abstract. Optical fiber is a material that can transport light signals, so resulting useful for data transmission and sensing applications. Fiber Bragg Gratings (FBG) are a specific type of optical sensors that can measure parameters like temperature, strain, and vibration. The PhD program focuses on developing a sensing and monitoring strategy for aerospace systems using FBG sensors networks. The study will include material selection, optical fiber manufacturing, sensors packaging and integration, calibration and interrogation techniques and smart logics development for acquiring and controlling phenomena affecting the equipment under test. Some experimental activities have already been conducted to analyse thermal and mechanical sensing and to define a reliable methodology for integrating sensors into various systems. During the tests, FBGs were found to have high accuracy and sensitivity for thermal variations, mechanical strain and short-term thermal transients. The crucial role of bounding technique was also enhanced. Additionally, more complex tests have been conducted for sensor more realistic systems, both for space and aeronautic environments. The results gained in this first period are positive and encouraging, suggesting further developments during PhD program.

Introduction

The optical fiber is a glass and polymeric material that can conduct a light signal inside itself. This particular feature has revolutionised the methodology of transporting data and information. The advent of optical fiber has therefore transformed communications technology, starting with the Internet connection. However, its unique physical characteristics have allowed it to be applied to a much wider spectrum in numerous and varied technical applications, and also in aerospace [1].

Optical fiber guarantees a high lightness and a small cross-section of its cables, combined with relatively low production costs. Moreover, it is immune to electromagnetic disturbances (a really crucial aspect for aerospace), while ensuring chemical and electrical passivity: consequently, it can guarantee high performances even in particularly hostile or potentially explosive environments. But the most interesting feature for engineering research is linked to the possibility of creating, directly within the fiber itself, optical structures that can act as sensors, measuring different parameters such as temperature, strain, vibration, humidity, etc... In fact, in the most frontier engineering projects the role of sensors is becoming increasingly important. Nowadays, they are required to not only provide a large amount of data with high accuracy, but also to correctly work in hostile environmental conditions. In aerospace, guaranteeing high performances in hostile environments is a typical requirement and optical-based sensors can meet it [2].

Generalities about optical fiber and FBG sensors

The optical fiber has a cylindric section with several concentric layers, from the inside to the outside, called *core*, *cladding* and *coating*. The external coating (together with eventual additional outer layers) is composed of a typical polymeric material and can vary depending on the application. Its purpose is solely to increase the mechanical features of the fiber, due to its extreme fragility. The core and cladding, on the other hand, are the two innermost glass layers that allow the fiber to transmit the light signal. In fact, if the light is entered in the core with a correct orientation, when it reaches the interface with the cladding it undergoes a total reflection, thus remaining confined to the fiber itself and so propagating the information. In general, core and cladding reach a diameter of 125 μm, which becomes 250 μm with the addition of a typical coating layer.

Optical sensors are created directly inside the fiber itself with techniques that vary depending on the type of sensors and their final application [3]. In this work only Bragg gratings (FBG) are considered. Although there are different techniques, they are generally produced by laser photoengraving. In this way, a periodic remodulation of the core's refractive index is created. This periodic remodulation acts as a filter against the electromagnetic radiation that passes through the fiber. All frequencies, in fact, pass through the grating, except for a specific frequency that is reflected. This frequency, called *Bragg frequency*, is quantified in terms of length as:

$$\lambda_b = 2n_{eff}\Lambda \tag{1}$$

Where n_{eff} is the refractive index of the section of the core containing the grating and Λ the physical distance between one remodulation and the following, called *grating pitch*. It is precisely the dependence of the Bragg frequency on the grating pitch that allows to associate the wavelength variation detected by the optical instrument to the measurement of a physical parameter acting on the sensor itself. On a general level, considering the temperature and the mechanical strain, the two quantities able to physically deform the sensor, the general equation of the FBG sensor results to be:

$$\Delta\lambda = K_T \Delta T + K_\varepsilon \Delta\varepsilon \tag{2}$$

where $\Delta\lambda$ is the variation of the reflected wavelength, K_T and K_ε are the correlation coefficients that allow the optical output to be converted into a temperature/strain value.

Optical fiber and FBG sensors for aerospace

The physical characteristics of the optical fiber, together with the possibility of embedding sensors inside itself, has aroused a significant interest in research also for the aerospace industry. Several studies are available in the literature on this subject, covering different application areas. A first example is represented by structural monitoring: thanks to the minimal fiber's diameter, it results suitable to create "smart" components, integrating the cable into the material during the manufacturing process [4], [5]. This technique can be used for both metallic and composite pieces, albeit with a different methodology. More in details, optical fiber can provide surface information either directly adhering to the structure, by acting as an "*optical strain gauge*" [6], [7]. Another intriguing aspect is the possibility of using FBGs to monitor temperature and structural integrity in remote locations or explosive environments (such as tanks). Because of the fiber's electrical passivity and inability to generate sparks, it is particularly well suited for this type of application, in which traditional sensors cannot be used.

Finally, thermal sensing is a significant field of interest for FBGs. The small fiber cross-section reduces the disturbance introduced by the sensor, which is a significant advantage over a traditional sensor. This could be especially important for thermal testing in space applications, where very thin layers must be tested. More broadly, many aerospace systems require temperature or other information in remote locations (i.e. insight servo-mechanism [8]), for which FBGs may be the best solution [9]. Furthermore, they appear to be suitable for cryogenic as well as high temperature applications. Nowadays, thermocouples with high thermal resistance are primarily used for this application. However, they degrade due to high-temperature oxidation, erosion, and contaminant intrusion into the probes and wiring, resulting in inaccuracies of up to 50°C. Because silica fibers can now withstand thermal cycling at temperatures close to 1000°C with a life time far superior to traditional sensors, optical sensors hold great promise for the development of new high-temperature resistant measuring systems [10].

This brief overview of possible FBGs aerospace applications explains solutions that appear to be extremely strategic. However, they are primarily laboratory-based studies and testing campaigns that have yet to be implemented in real-world systems. Furthermore, there is currently no standard procedure for integrating FBG and optical fibers in aerospace systems and/or components.

Optical sensor networks for aerospace systems lifecycle management

The overall activity about PhD program (Fig. 1) is focused on the study of optical fiber sensors networks, integrated with other traditional sensors, to realize a sensing and monitoring strategy for aerospace systems along the whole development lifecycle. To do this, at first, a methodology to define a network optical multi-sensor chain will be developed for the acquisition of different quantities on the basis of the application (space or aeronautics). In this phase, special attention will be dedicated to the material selection, the optical fiber manufacturing, and sensors packaging and integration, taking into account the environmental characteristics: level of vibration, temperature, atmosphere pressure, etc…

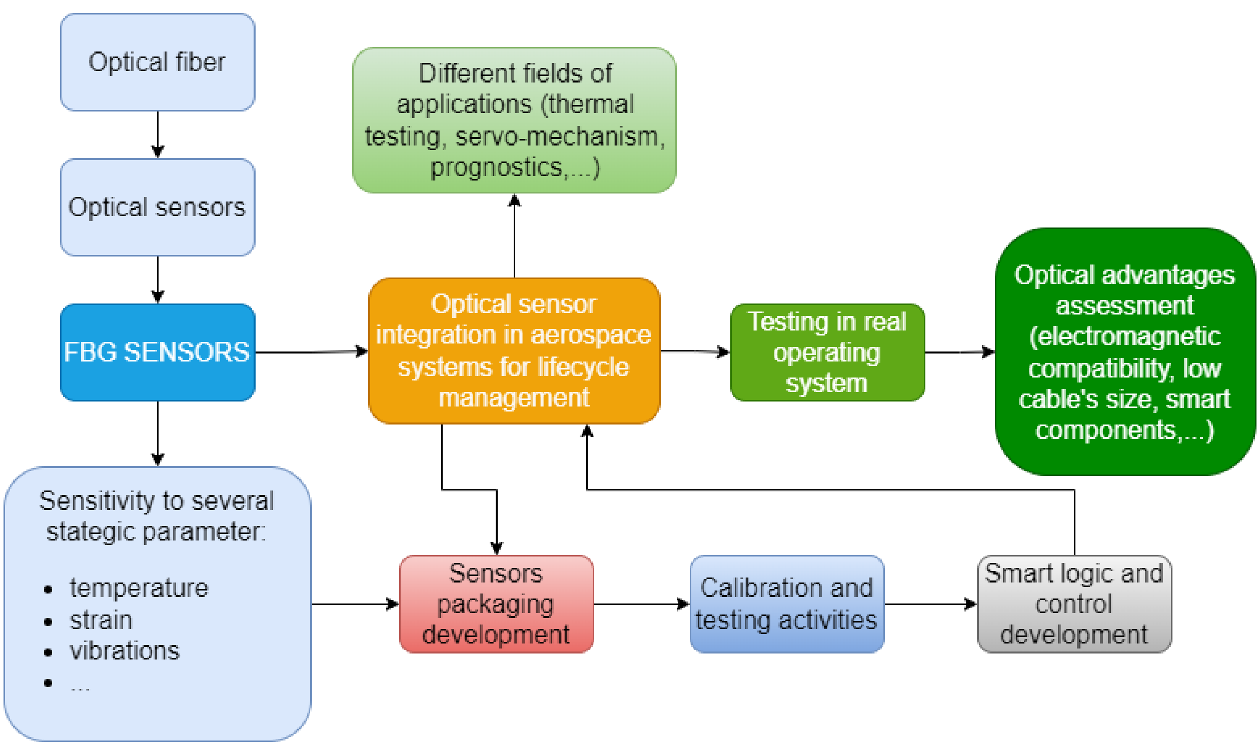

Figure 1. Scheme resuming the overall approach to research activities

Then, the study of the calibration and the interrogation techniques (data storage) of the sensing network will be performed, also using the correlation of data produced by different type of sensors, not necessarily based on the optical technology, that supports the measures and increase the confidence level. Finally, the definition of a set of techniques to interpret the data drawn from the sensing network will be developed. Depending on the applications (servomechanisms, on board systems, thermal testing, etc..) smart logics will be developed to acquire quantities the are useful to capture and control some phenomena affecting the equipment under test. Special emphasis will be addressed to diagnostic and prognostic strategies for a defined aerospace system along the whole development lifecycle.

Some experimental activities have already been carried out, in order to have enough know-how to define a standard and reliable methodology for sensors integration in the systems of interest. In particular, the experimental activities currently conducted are divided into three main areas, in which FBGs were bounded on:

• *samples* for laboratory tests about thermal and mechanical sensing;
• a *model aircraft* for structural monitoring and real time data transmission;
• *space MLI* for thermal testing in vacuum.

Laboratory tests covered sensitivity analysis of FBG sensors to temperature variations and mechanical strain when applied to typical aerospace materials. In particular, great attention has been paid on a *gluing methodology* and to the *sensor reaction time*.

As previously stated, the Bragg wavelength, which is nominally defined during the manufacturing phase by the grating etching process, can vary as a result of physical changes in the sensor itself or environmental conditions (physical stresses applied to the grating or variations of temperature). To ensure satisfactory levels of accuracy and reliability, the correlation of the Bragg wavelength variation with these variations is required. At first, the sensitivity of the Bragg gratings to temperature changes was verified, varying the materials used, the environmental conditions of measurement and the bonding technique. The experimental data collected were used to perform the thermal calibration of the sensors used. The influence of boundary conditions on the sensor calibration process was then defined. Moreover, the FBG sensitivity to environmental temperature conditions is also a fundamental aspect when the same optical sensors are used for other measuring purposes. In fact, the main criticality of FBG is represented by the *cross-sensitivity*: the sensor provides a single optical output, whose variation may depend on multiple factors that the sensor is exposed to. In particular, using FBGs as mechanical strain sensors, it is crucial to estimate with proper accuracy the disturbance generated by other factors (such as temperature) and conceive an effective compensation method. Tests highlighted a very precise linear relationships between optical output and thermal/mechanical stresses applied on the sensor. In this way, the correlation coefficients have been experimentally calculated and, thanks to them, the over lapping process could be used to filter data. The technique to decouple the different contributions is still under investigation, due to the significative complexity of the process. The simplest strategy, already applied with great successful results (Fig. 2), consists in three different steps. At first, an optical sensor is thermically calibrated. Then, after it has been placed on the component for mechanical measures, it is flanked by a second sensor. This second sensor is not mechanically stressed and it provides only the temperature value: in this way, data from first sensor can be filtered by the thermal contribute. The second sensor, essential for the decoupling process, could be electronic or optic.

The results highlighted how, once the wavelength trend is filtered from the contribution of the environmental conditions, FBG could read mechanical strain with high level of accuracy. Furthermore, during the test campaign different bounding techniques were compared. In particular, the effects of a fiber pre-tensioning were analysed. The results showed a possible influence on the correlation coefficients, but with minimal difference on the final accuracy.

Finally, it was tested the FBG capability to read short-term thermal transients, by comparing performances with a conventional thermal probe (PT100). The campaign showed that optical sensors have an extremely high sensitivity and a much shorter reaction time. Data collected allow to consider strategic the use of FBG for thermal monitoring, above all considering the fiber minimally invasiveness and high accuracy.

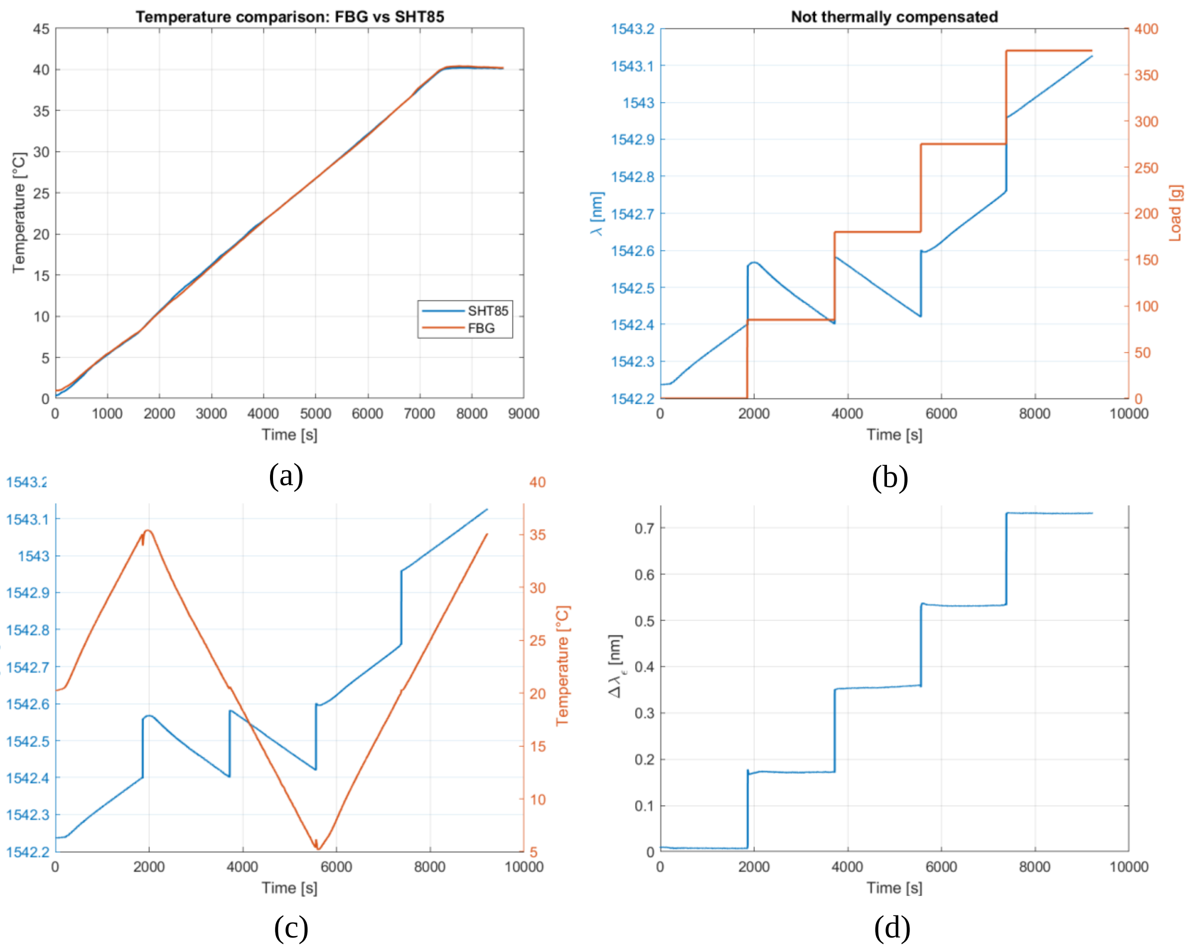

Figure 2. Comparison between temperature sensing of FBG and electronic sensor (a), FBG output when mechanical loads and thermal variation contextually act on the sensor (b,c) and after thermal compensation (d).

After verifying the high sensitivity of FBG sensors, some more complex activities have been conducted for starting to sensor example of aerospace systems.

A first application was to install some FBGs along the wing of a model aircraft made of composite materials. So, it was created a flying experimental test bench for testing performances of monitoring aircraft systems with optical technology and to develop the electronic system for transmitting data to ground in near real-time [11]. Thanks to a great work developed with a multi-disciplinary team, an integrated open-source solution was proposed. Using data detected by FBG, the system is able to display the temperature and displacements of the structure on a heat map arranged on a 3D model and visualized through a computer application on the ground. The methodology can be applied to various scenarios, ranging from maintenance planning activities to performance checks, providing an all-in-one solution for flight data management and structural monitoring.

The last field of application in which some tests have already been conducted is thermal testing for space. In particular, the reliability and sensitivity of FBG sensors for temperature measurements in a thermal protection system (MLI) were tested, comparing performances with thermocouples. From experimental data it was found that optical sensors have several advantages, including lower noise in terms of heat flow and faster reaction time. However, tests have also demonstrated the extreme importance of the methodology of integration of optical sensors, which could be critical and source of inaccuracy above all at low temperatures.

Results and further development

Some extremely positive and encouraging results have already been achieved in this first doctoral period. In particular, these refer to the high sensitivity shown by optical sensors, even when applied to materials of typical aerospace environment and in hostile environmental conditions. The physical advantages of fiber, together with the ability to measure different physical parameters with the same instrument, make optical sensors particularly interesting for aerospace.

However, some important issues still need to be properly studied and deepened. First of all, it is necessary to have a standardized procedure of gluing, packaging and calibration of the sensor, in order to fully comply with industry regulations. Secondly, a uniquely tested technique must be developed to overcome the problem of sensor cross sensitivity. Finally, it is necessary to verify on real operating systems what is currently verified by laboratory tests.

References

[1] A. Behbahani, M. Pakmehr, and W. A. Stange, “Optical Communications and Sensing for Avionics,” in *Springer Handbooks*, Springer Science and Business Media Deutschland GmbH, 2020, pp. 1125–1150. doi: 10.1007/978-3-030-16250-4_36.

[2] S. J. Mihailov, “Fiber Bragg Grating Sensors for Harsh Environments,” *Sensors*, vol. 12, pp. 1898–1918, 2012, doi: 10.3390/s120201898.

[3] S. J. Mihailov *et al.*, “Ultrafast laser processing of optical fibers for sensing applications,” *Sensors*, vol. 21, no. 4. MDPI AG, pp. 1–23, Feb. 02, 2021. doi: 10.3390/s21041447.

[4] R. P. Beukema, “Embedding Technologies of FBG Sensors in Composites: Technologies, Applications and Practical Use.”

[5] F. Heilmeier *et al.*, “Evaluation of strain transition properties between cast-in fibre bragg gratings and cast aluminium during uniaxial straining,” *Sensors (Switzerland)*, vol. 20, no. 21, pp. 1–19, Nov. 2020, doi: 10.3390/s20216276.

[6] H. Wang, S. Li, L. Liang, G. Xu, and B. Tu, “Fiber grating-based strain sensor array for health monitoring of pipelines,” *SDHM Structural Durability and Health Monitoring*, vol. 13, no. 4, pp. 347–359, 2019, doi: 10.32604/sdhm.2019.05139.

[7] Q. Zhang, D. Zhang, J. Li, B. Shui, and Y. Guo, “Strain measurement inside a strong pulsed magnet based on embedded fiber Bragg gratings,” in *OFS2012 22nd International Conference on Optical Fiber Sensors*, Oct. 2012, vol. 8421, pp. 84213P-84213P–4. doi: 10.1117/12.966334.

[8] D. Belmonte, M. D. L. Dalla Vedova, and P. Maggiore, “Prognostics of onboard electromechanical actuators: A new approach based on spectral analysis techniques,” *International Review of Aerospace Engineering*, vol. 11, no. 3, pp. 96–103, 2018, doi: 10.15866/irease.v11i3.13796.

[9] E. J. Friebele *et al.*, “Optical fiber sensors for spacecraft applications,” *Smart Mater. Struct*, vol. 8, pp. 813–838, 1999, Accessed: Feb. 01, 2023. [Online]. Available: www.iop.org

[10] M. Pakmehr and A. Behbahani, “*Optical Exhaust Gas Temperature (EGT) Sensor and Instrumentation for Gas Turbine Engines Advanced Pressure Sensing for Gas Turbine Engines View project Intelligent systems View project*”, doi: 10.14339/STO-MP-AVT-306-18-PDF.

[11] A. C. Marceddu *et al.*, “Air-To-Ground Transmission and Near Real-Time Visualization of FBG Sensor Data Via Cloud Database,” *IEEE Sens J*, 2022, doi: 10.1109/JSEN.2022.3227463.