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Preliminary design and performance evaluation of optical fiber-based load sensor for aerospace systems

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Abstract. This paper describes a new Fiber Bragg Grating (FBG) optical sensor conceived for load measurements in harsh aerospace environments. This sensor combines miniature size, durability, and precision, making it ideal for aerospace applications with extreme temperatures, vibrations, and mechanical stresses. The proposed sensor combines the peculiarities of the traditional load cells with the well-known advantages due to the use of optical fibers. The paper describes the layout, fabrication and performance characteristics of this sensor design. The used materials and the compact packaging enable its integration into space-constrained aerospace systems without compromising performance. The preliminary experimental results demonstrate its potential under various load conditions, validating their applicability in real-world aerospace scenarios; it addresses a critical need for robust and compact load measurement solutions, contributing to the advancement of aerospace technology. This work demonstrates the feasibility of the proposed concept and defines the functional requirements that must be satisfied by future developments of this type of sensor.

1. Introduction

In modern engineering research projects, an increasingly significant role is played by innovative sensors capable of combining high performance (such as sensitivity, accuracy, and reliability) with the ability to withstand external disturbances, thus well operating in hostile environments [1]. Fiber Bragg Grating (FBG) sensors meet these requirements [2], [3]. In particular, their immunity to electromagnetic interferences, lightness, and ability to operate in the presence of high thermal excursions make them particularly suitable for the aerospace sector [4], [5].

This article discusses the development of an innovative sensor for measuring the force applied to a surface using an FBG (Fig. 1). As known, Bragg gratings are directly inscribed inside an optical fiber using a laser photo-inscription technique [6]-[9]. Specifically, considering the typical multilayer structure of a single-mode optical fiber, over a short length of approximately 1 cm, the innermost layer undergoes a periodic modulation of its refractive index (Fig. 2). This process creates, at regular intervals, bands of material with refractive index alternating between n and n+Δn. The set of material bands with different refractive indices is the FBG sensor. The constant and regular distance between a band with the modified index n+Δn and the next one is the main sensor characteristic, called the grating pitch (Λ).

This particular structure, when traversed by an electromagnetic spectrum, behaves like a filter: indeed, all frequencies contained in it pass through, except for a specific frequency that is reflected in the opposite light beam propagation direction. This reflected frequency, called the Bragg frequency, is the sensor's output and is quantified in terms of wavelength according to:

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

As can be clearly observed, the Bragg frequency is directly proportional to the grating pitch. Since the grating pitch is a physical length, any external factor that modifies this length results in a variation of the frequency reflected by the grating. For this reason, FBG sensors are primarily used to monitor temperature changes and mechanical deformation [10]-[12], since these are the two main physical parameters influencing the variation in grating pitch length. From a mathematical perspective, the variation in wavelength (hereafter, the Bragg frequency will always be expressed as wavelength) reflected by the sensor is quantified as follows:

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

where $\Delta\lambda/\lambda$ is the parameter measured by the provided instrumentation. When an FBG sensor is applied to the piece under monitoring, it can be clearly observed that the value of $\Delta\lambda/\lambda$ it provides depends on the combination of two contributions:

- The variation in temperature ΔT;
- The mechanical deformation $\Delta\varepsilon$.

It can be clearly deduced, therefore, the capability of FBGs to be sensitive to different physical parameters while exploiting the same operating mechanism.

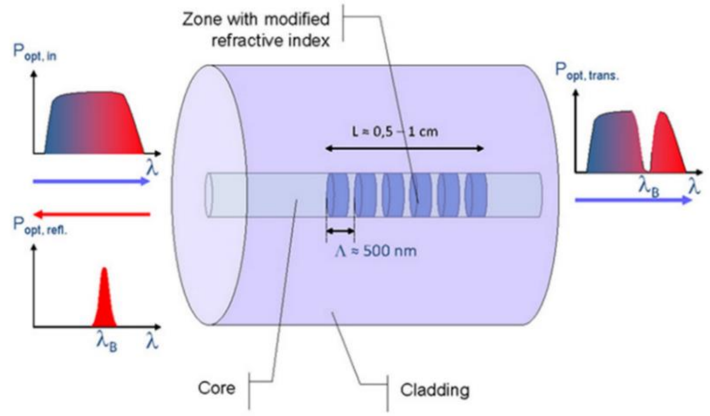

Figure 1. FBG working principle

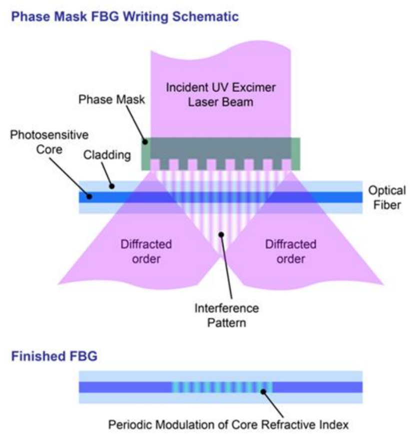

Figure 2. FBG creation process

2. Materials and methods

The application focused on the development of an innovative load cell sensor for estimating applied force exploiting the minimal invasiveness of FBG sensors. Specifically, a sensor was embedded inside a cylinder made of deformable polymeric material. This material, when subjected to an axial compression load perpendicular to the direction in which the axis of the optical fiber is placed, undergoes a strain in the direction orthogonal to the load application. This is a consequence of the so-called Poisson effect and, therefore, the resulting force is aligned with the fiber orientation. In this way, the Bragg grating can be sensitive to an axial load (Fig.3).

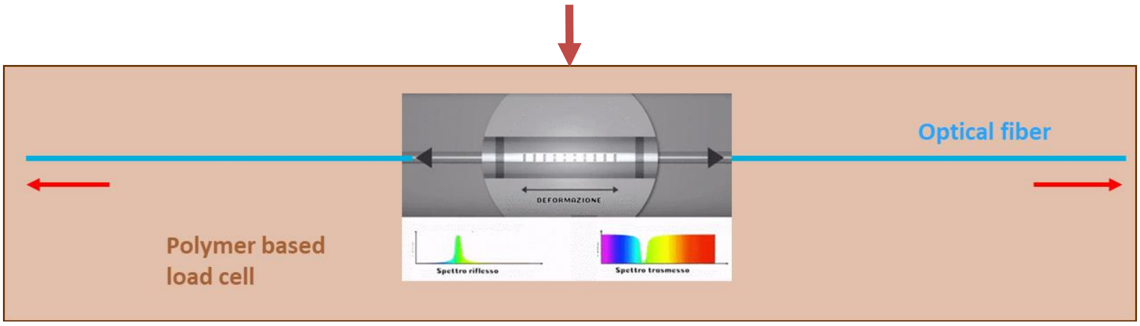

Figure 3. Logic of load cell working principle

The sensor implementation and its performances verification were carried out in 3 phases:

- Realization of the Optical Fiber Section and Data Acquisition System;
- Integration of Optical Fiber into the Support Material;
- Testing campaign.

2.1 Optical hardware and data acquisition system

As specified in the introduction, the work is based on the FBG use. In particular, a grating resulting from a laser photo-inscription process applied to a single-mode optical fiber was adopted. The fiber is coated with polyacrylate with an overall diameter of 250 µm. Additionally, to physically read the data, it was necessary to splice the optical fiber section containing the FBG with an FC\APC-type connector. This operation was carried out using a dedicated machine called Fusion Splicer (Fig. 4), specifically the Fujikura ArcMaster FSM-100P+. The junction is automated by the tool, generating a high-temperature electric arc, thus melting the two ends and effectively joining them into the same fiber section.

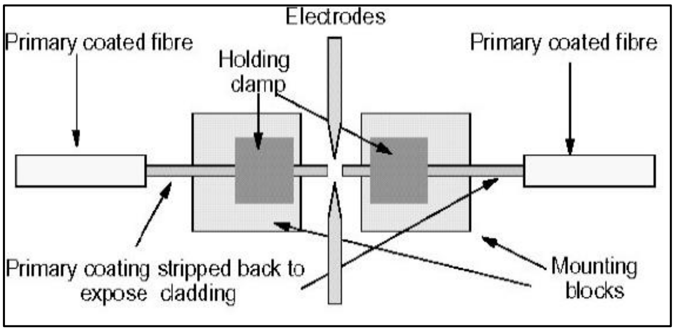

Figure 4. Fusion splicer structure.

Lastly, the data acquisition system relies on the use of a specific tool, known as an Interrogator. It allows the generation of a light beam that is entered iside the optical fiber through the FC/APC connector.This light beam, as known, passes through the FBG sensor, except for the Bragg frequency, which is reflected and quantified by the interrogator. Via an Ethernet cable, the interrogator sends the data of the reflected frequencies to the PC, enabling the user to have the final measurement. In this work, a Smart Scan interrogator from the company Smart Fibers was employed.

2.2. Final sensor assembly process

Once assembled the optical hardware, the sensor was created through the following steps:

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1. Definition of a three-dimensional mold created using additive manufacturing techniques.
2. Insertion of optical fiber equipped with a Bragg grating and passing it through the mold, taking care to place the instrumented area at the midpoint of the mold.
3. Casting of resin into the mold.
4. Removal of the mold.

2.3 Test campaign organization

During the experimental activities, different sensor's prototypes were developed, each one with specific properties. In particular, due to the preliminary nature of this analysis, parameters involved were mainly based on the overall geometry and on the materials employed around the FBG. More in details, three configurations here are analysed:

- FBG sensor put in silicon resin with a first geometry mold.
- FBG sensor put in silicon resin with a second geometry mold.
- FBG sensor put in epoxy resin with the second geometry mold.

The three developed configuration were tested in a specific bench developed at Politecnico di Torino (Fig 5). In particular, it refers to the development of a brake for small aircrafts: this is realized by employing a specific electro-mechanical actuator (EMA). In this regard, an electronic load cell was placed in a specific flange for assessing the overall brake performances, in terms of load applied by the EMA. The optical load cell described in this work was so integrated in the same allocation in order to assess its performances.

Figure 5. Test bench

3. Results and discussion

Considering that the sensor development process involved three different configurations, in this chapter the results are analyzed separately for each prototype.

3.1 First prototype

The first prototype, shown in Fig. 6, was created using a support of generic geometry, without dimensioning it for a specific application. The purpose of this first prototype was to validate the proof of concept, verifying the sensitivity of the sensor as a whole to the application of a progressively increasing load. The results of this initial configuration were already significant and positive, although still considered partial.

The application of an axial load led to observe a sensor response consistent with the hypothesis. In particular, the experimental test campaign highlighted an extreme sensor's reactivity to solicitations. Additionally, the detected optical response proved to be linear in function of the applied load. Finally, the sensor development process showed to be quite simple to be realised.

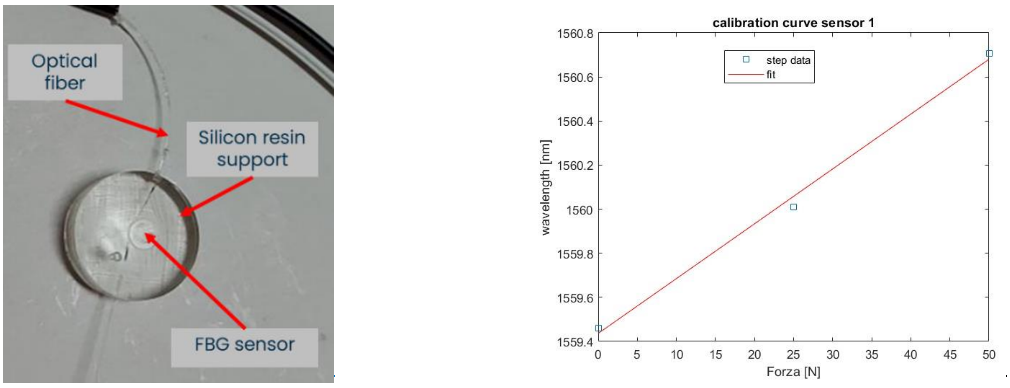

Figure 6. First prototype and its calibration curve

The current geometry, however, has encountered a rather significant limit in terms of operating range, attributable to a maximum nominal value not exceeding 50N. For this reason, further geometries were developed.

3.2 Second prototype

In order to broaden the sensor operational range, the geometry of the support was redesigned. After a careful performance analysis of the previous configuration, it became necessary to increase the supporting surface of the sensor to extend the actuator's stroke and, consequently, increase the operational range of the prototype. The modification to the geometry was implemented through two specific steps (Fig.7). Firstly, the size of the housing for the load cell provided by the flange on the experimental bench was precisely adopted. Then, an additional layer of material was added to the base of the sensorized cylinder to increase the resistance between the piston and the sensor. This additional layer, counteracting the actuator's tendency to reach the end of its stroke, allows the sensor to read loads significantly higher than in the previous case. In Fig. 8, an example of the obtained response can be observed, showing significant advancements in the guaranteed performance.

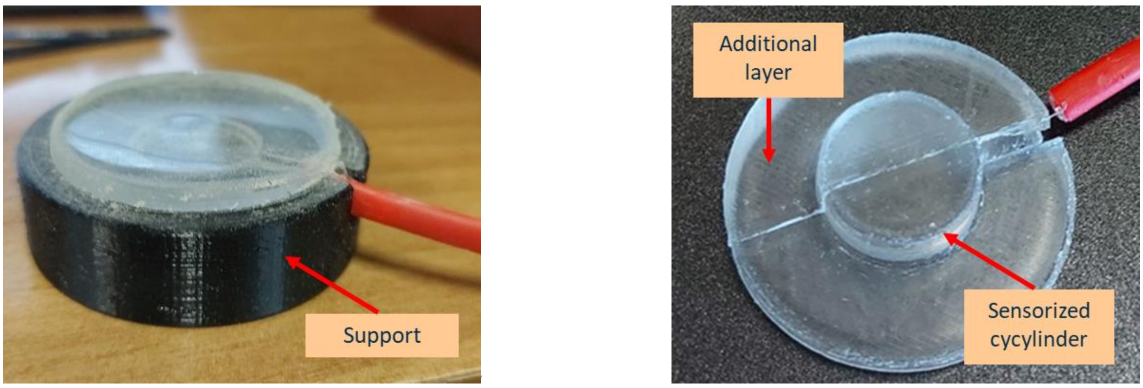

Figure 7. Second prototype

Particularly, an extremely fast, repeatable, and reversible response is maintained during repeated and closely spaced cycles of loading and unloading of the sensor itself. However, the added geometry, while allowing a significant improvement in the operating range up to about 200 N, has proven to be still critical regarding the housing in the flange of the experimental bench. In fact, despite the cylinder's geometry being designed based on the available housing, the additional layer of material has made the insertion and removal process challenging.

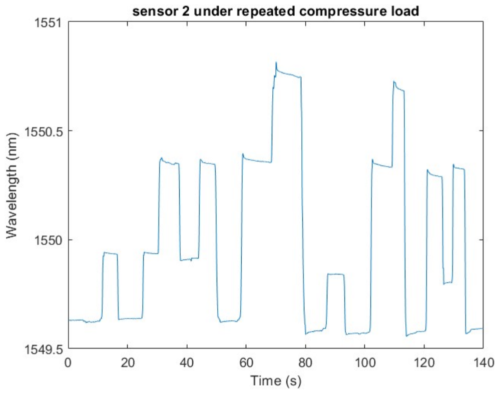

Figure 8. Example of sensor output during a test

3.3 Third prototype

Due to the need to combine a geometry well adhering to the metal flange of the experimental bench with the possibility of increasing the measurable force range through the developed sensor, a third sensor model was created. In this case, the same procedure as the first prototype was used, but the resin employed was varied, opting for epoxy resin. The goal of this final configuration was to make the sensor as similar as possible to the electronic load cell (Fig. 9).

The results obtained with this configuration proved to be significant and positive. Good sensor reactivity was demonstrated, although the response time is greater compared to the previous case. However, thanks to this configuration, it was possible to reliably extend the range of use up to 200 N, but still able to reach values of about 700 N, beyond which the probe loses sensitivity. Fig. 10 shows the calibration steps of the FBG sensor. A predominantly linear trend emerging from the experimental data can be clearly identified, making the sensor easily integrable into the experimental setup and the outgoing data flow from the test bench.

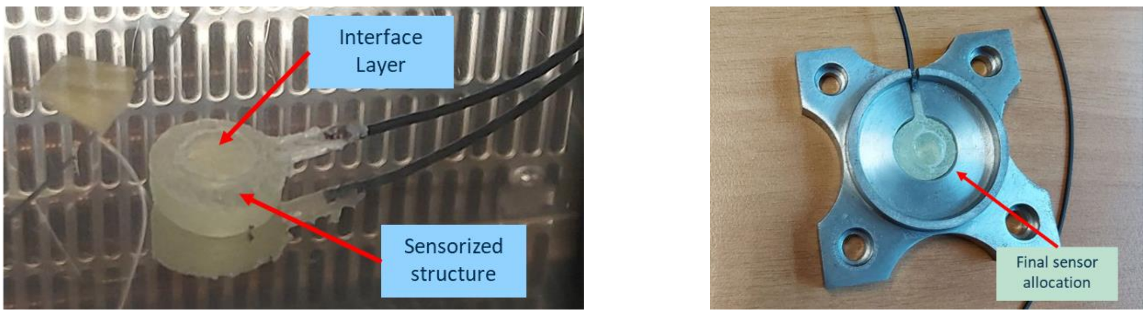

Figure 9. Third prototype

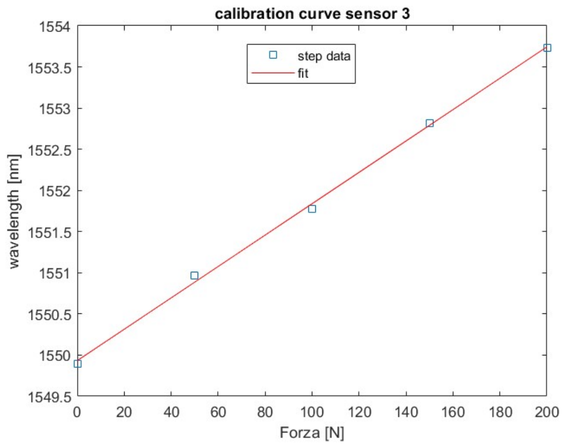

Figure 10. Third prototype calibration curve

4. Conclusions and future steps

In the present work, it was possible to verify the innovative proof of concept related to the development of a load cell using FBG sensors. Specifically, an optical fiber, containing a FBG sensor, was embedded in a polymeric material. This one, as it deforms due to the application of a load, transfers the deformation to the FBG sensor, whose reflected frequency change is correlated with the load applied to the structure.

In order to maximize both the sensitivity of the sensor and the range of applicability (both in terms of read load and geometric application), different configurations were proposed and analyzed. In all cases, however, it was possible to observe a linear response of the FBG sensor to the applied load. Conversely, different ranges of applicability and variations in sensor response time were found depending on the geometry and type of resin used. Consequently, having verified through this work the excellent prospect related to the use of optical sensor technology for load cell development, it is necessary to conduct a more in-depth investigation in order to identify materials and geometries that can maximize the achievable results. In addition, a detailed analysis of these parameters may also allow numerous variants of the same concept to be defined in order to offer an application that could be integrated into systems with even very different requirements.

Finally, most of the future developments could be linked to the computer integration of the optical interrogator with the control logic of the entire test bench. This could ensure the use of optical data directly in the brake control loop, allowing the simultaneous exploitation of the physical advantages of fiber combined with high sensitivity and reaction time to changing physical conditions.

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