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Composite structural panel natural frequencies estimation by Fiber Bragg Grating sensors network

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***Abstract*—The identification of the dynamic properties of composite structures is a key aspect for both structural validation and structural health monitoring in aerospace applications. In this work, the capability of Fiber Bragg Grating (FBG) sensors to identify the natural frequencies of a composite plate is experimentally investigated. An optical sensing network composed of multiplexed FBG sensors was externally bonded to the surface of the plate using a simple industrial Kapton adhesive, enabling a plug-and-play sensing configuration. Impact hammer tests were performed in order to excite the structure, and the resulting dynamic strain signals measured by the FBG sensors were processed through frequency-domain analysis to extract the modal frequencies. The obtained results were compared with those measured using a traditional accelerometer-based system adopted as reference instrumentation. The experimental results show an excellent agreement between the two measurement approaches, with discrepancies below approximately 2% for frequencies up to $300Hz$. The results confirm the potential of FBG-based sensing systems for dynamic monitoring of composite structures and open the possibility of developing smart composite panels capable of real-time vibration monitoring for advanced structural health monitoring applications.**

***Index Terms*—Fiber Optic senors; aerospace; structural health monitoring, smart structure**

I. Introduction

Composite materials have become a key enabling technology for modern aerospace structures due to their high specific strength, high specific stiffness, and excellent fatigue and corrosion resistance [1]. Compared with traditional metallic materials such as aluminum and titanium alloys, fiber-reinforced composites allow engineers to design lightweight structures with tailored mechanical properties by controlling the orientation, stacking sequence, and type of reinforcement fibers [2]. These characteristics make composite materials particularly attractive for applications where weight reduction and structural efficiency are critical design drivers [3]–[5].
Among the different classes of composite materials, carbon fiber reinforced polymers (CFRPs) are currently the most widely adopted in aerospace applications. CFRPs combine high-modulus carbon fibers with polymeric matrices such as epoxy resins, resulting in structures that exhibit excellent stiffness-to-weight ratios and good environmental resistance. Other composite systems used in aerospace include glass fiber reinforced polymers (GFRPs), which offer lower cost and good impact resistance, and aramid fiber composites, which provide high toughness and damage tolerance. These materials are extensively employed in primary and secondary aircraft structures, including wings, fuselage sections, control surfaces, satellite panels, and rotor blades in helicopters. In recent aircraft generations, such as the Boeing 787 and Airbus A350, composite materials account for more than 50% of the total structural weight. [6]

Despite their advantages, composite structures introduce new challenges in terms of structural monitoring and damage detection. Unlike metallic structures, composites may exhibit complex failure mechanisms such as matrix cracking, delamination, fiber breakage, and interlaminar debonding, which are often difficult to detect through conventional inspection techniques. For this reason, the development of reliable structural health monitoring (SHM) systems has become an important research topic in the aerospace field. SHM approaches aim to continuously or periodically monitor the structural state by integrating sensors within or on the surface of the structure. Among the most commonly adopted sensing technologies are piezoelectric transducers, strain gauges, accelerometers, and acoustic emission sensors. These systems allow the detection of dynamic responses, strain fields, and damage-induced changes in the structural behavior [7]–[9].

One of the most informative parameters for evaluating the structural integrity of a component is its dynamic response, and in particular its natural frequencies and mode shapes. The modal properties of a structure are directly related to its mass and stiffness distribution. Therefore, the presence of damage, defects, or structural degradation typically leads to

measurable variations in the natural frequencies and damping characteristics. Experimental modal analysis techniques, such as impact hammer testing combined with accelerometer measurements, are widely used to estimate the natural frequencies of structures and to validate numerical models. In aerospace applications, these techniques are essential for verifying the dynamic behavior of lightweight structures and ensuring compliance with design requirements.

In recent years, fiber optic sensing technologies have emerged as a promising alternative to traditional electrical sensors for structural monitoring applications. Among these technologies, Fiber Bragg Grating (FBG) sensors have received significant attention due to their intrinsic advantages. FBG sensors are lightweight, immune to electromagnetic interference, resistant to harsh environmental conditions, and capable of multiplexing multiple sensing points along a single optical fiber. These characteristics make them particularly suitable for aerospace applications, where sensor weight, wiring complexity, and reliability are critical factors. [10]–[12] FBG sensors measure strain by detecting shifts in the reflected Bragg wavelength of the optical grating embedded within the fiber. When bonded to a structure, the mechanical strain experienced by the surface is transferred to the optical fiber, producing a measurable change in the Bragg wavelength. This property enables FBG sensors to capture dynamic strain signals associated with structural vibrations. Consequently, they can be effectively used to estimate the natural frequencies of vibrating structures [13]. The use of FBG sensors for experimental modal analysis offers several advantages compared with conventional accelerometer-based systems. First, the extremely small size and low mass of optical fibers minimize the influence of the sensor on the dynamic response of lightweight structures. Second, the possibility of multiplexing multiple sensors along a single fiber significantly reduces cabling complexity and simplifies instrumentation of large structures [14]–[16]. Finally, optical sensing systems allow distributed measurements over wide areas of a structure, enabling more comprehensive monitoring of its dynamic behavior. Several studies demonstrated the capability of Fiber Bragg Grating sensors to perform modal identification and dynamic monitoring of composite structures [17]–[19].

For these reasons, the investigation of FBG-based sensing systems for the identification of natural frequencies in composite structures represents a relevant research topic for aerospace structural monitoring [20]. The present work aims to experimentally evaluate the capability of an FBG sensor network, externally bonded to a composite plate using a simple adhesive interface, to detect the natural frequencies of a structural plate through impact hammer testing. The obtained results are compared with those measured using traditional accelerometer-based instrumentation in order to assess the reliability and effectiveness of the proposed optical sensing approach.

II. Materials and Methods

The research activity described in this work aims to verify the capability of measuring the natural frequencies of a composite plate through the integration of a network of optical FBG sensors. In particular, the objective is to test the reliability of the optical system when the sensor array is simply placed in contact with the external surface of the structure and fixed using a standard industrial adhesive tape (Kapton). The overall experimental approach consisted of performing a classical Hammer test on the component using both traditional instrumentation and optical instrumentation, in order to compare the obtained experimental results. In both tests, the plate was positioned on a highly compliant cylindrical foam support, in order to reproduce as realistically as possible the free–free boundary condition. Nine measurement points were identified on the surface of the plate for the detection of the natural frequencies, as shown in Fig. 1.

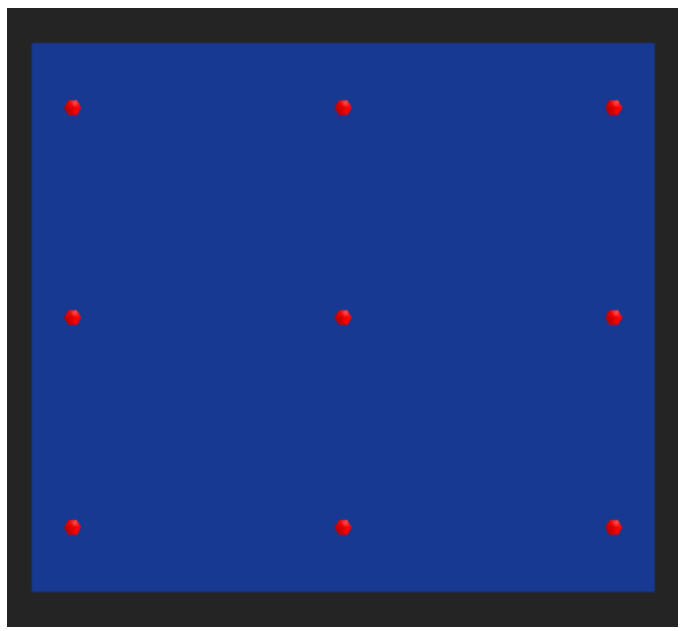

Fig. 1. Measurement Points

The first step involved the creation of the optical measurement chain. This was implemented by multiplexing three FBG sensors along a single optical fiber with an acrylate coating and a diameter of 250 μm. The wavelengths of the three sensors were properly selected in order to avoid possible interference and spectral overlapping. The fiber was fixed at the measurement points using Kapton adhesive dots. For operational simplicity, a single optical fiber with three sensors was used; the sensor array was repositioned three times and the acquisition process was repeated for each configuration. Figure 2 shows the plate instrumented with the optical sensor network.

The optical measurement chain was completed by the following instrumentation:

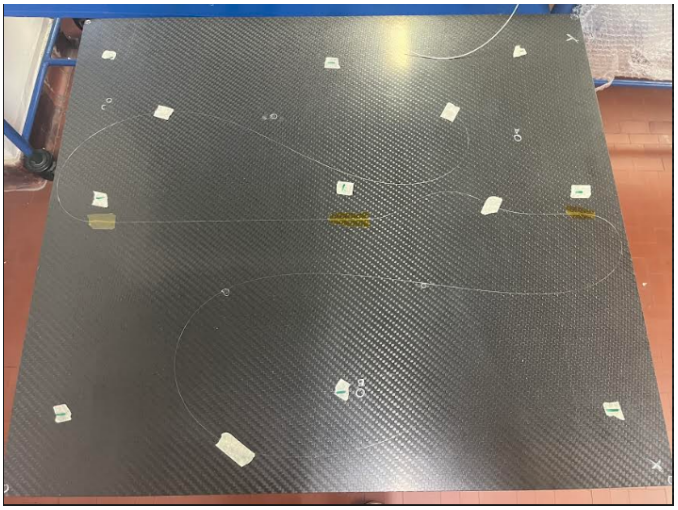

Fig. 2. Plate instrumented with the optical sensor network

- an instrumented hammer for the Hammer test;
- an FBG interrogator;
- a host PC for data storage and processing.

In order to compare the capability of the FBG sensors to measure the natural frequencies of the system, a traditional measurement system based on accelerometers was implemented as a reference.

The instrumentation included:

- an instrumented hammer;
- piezoelectric accelerometers;
- accelerometric acquisition software.

Figure 3 shows the plate with both FBGs and accelerometers sensors.

For both configurations, two excitation points were identified on the plate where the hammer impacts were applied. The test consisted of acquiring data from all nine instrumented measurement points. Moreover, in order to reduce uncertainties related to the manual hammer impact, the excitation was repeated five times at each position.
Regarding the acquisition performed using piezoelectric accelerometers, the testing procedure consisted of repeating the five impacts at both excitation points while ensuring the proper quality of the hammer strike. In the case of an imprecise impact or an excessively large amplitude, the acquisition software required the repetition of the test. The five measurements were first averaged in the time domain and then processed through FFT in order to compute the frequency spectrum. The natural frequencies were identified as peaks in the obtained spectrum. For the acquisition performed using FBG sensors, the testing procedure remained substantially the same, but with the significant difference that the interpretation logic of the optical data had to be fully defined. It should be recalled that an FBG sensor provides as output a wavelength value, known as the Bragg wavelength, which under standard environmental conditions is defined as:

Fig. 3. Plate with both optical and piezoeletric sensors.

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

where n represents the average refractive index in the sensing region and Λ the grating period. From this relation the well-known equation follows:

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

Neglecting temperature variations, the entire optical variation measured by the instrumentation can therefore be fully attributed to the mechanical strain experienced by the sensor.

In the present case, considering the high stiffness of the plate, the application of the Dirac delta excitation to the plate through the hammer induces oscillations of the structure. These oscillations generate shear stresses in the adhesive layer, which in turn transfer the load as an axial mechanical stress to the optical fiber, producing a local strain in the grating [21], [22].

From a mathematical point of view, after the impulse the response is a sum of the natural modes:

$$w(x,y,t) = \sum_n \phi_n(x,y), q_n(t) \tag{3}$$

where w is the out-of-plane displacement, ϕ_n is the mode shape, and $q_n(t)$ is the modal coordinate oscillating with natural frequency ω_n.

Assuming a Kirchhoff-Love plate model, the longitudinal strain on the surface is

$$\varepsilon_p(x,y,t) = -z\frac{\partial^2 w}{\partial x^2} \tag{4}$$

where $z = h/2$ is the distance from the neutral axis.

Therefore, the surface of the plate periodically stretches and contracts at the natural frequencies.

Let us now consider the plate–adhesive–fiber system characterized by the following parameters:

- (E_f) = Young's modulus of the fiber;
- (A_f) = cross-sectional area of the fiber
- (G_a)= shear modulus of the adhesive
- (t_a) = adhesive thickness
- (L) = bonded length

The plate imposes an axial displacement $u_p(x,t)$ on the surface, while the fiber experiences a displacement $u_f(x,t)$.

The relative displacement generates a shear stress in the adhesive:

$$\tau(x) = \frac{G_a}{t_a}(u_p - u_f) \tag{5}$$

The axial force in the fiber is

$$N_f = E_f A_f \frac{du_f}{dx} \tag{6}$$

Force equilibrium on a fiber element gives

$$\frac{dN_f}{dx} = \tau P \tag{7}$$

where P is the contact perimeter.

Substituting:

$$\frac{d}{dx}\left(E_f A_f \frac{du_f}{dx}\right) = P\frac{G_a}{t_a}(u_p - u_f) \tag{8}$$

which becomes

$$\frac{d^2 u_f}{dx^2} - k^2(u_p - u_f) = 0 \tag{9}$$

with

$$k^2 = \frac{PG_a}{E_f A_f t_a} \tag{10}$$

If the strain in the plate is

$$\varepsilon_p = \frac{du_p}{dx} \tag{11}$$

the solution of the differential equation leads to

$$\varepsilon_f(x) = \varepsilon_p\left(1 - \frac{\cosh(kx)}{\cosh(kL/2)}\right) \tag{12}$$

If the bonded length is sufficiently large $kL \gg 1$, we obtain

$$\varepsilon_f \approx \varepsilon_p \tag{13}$$

that is, the strain of the plate is almost completely transferred to the fiber.

Recalling Eq. 1 and Eq. 2:

$$\Delta\lambda_B(t) \propto \varepsilon_f(t) \tag{14}$$

Since

$$\varepsilon_f(t) \approx \varepsilon_p(t) \tag{15}$$

the wavelength variation therefore contains the same modal frequencies as the vibrating plate.

III. Results and Discussion

The first phase of testing was carried out to determine the reference natural frequencies using the accelerometer-based measurement system. The repetition of the test allowed the validation of the obtained results which, apart from minor variations in signal amplitude, consistently identified the same peak frequencies in the spectrum and therefore the same natural frequencies. Table III reports the frequencies measured using the accelerometers, while Fig. 4 shows the spectrum obtained from the instrumentation.

Table III
Natural Frequencies Obtained From Accelerometers

Mode n.	Frequency [Hz]
1	81.250
2	191.406
3	216.406
4	226.562
5	321.875
6	353.125

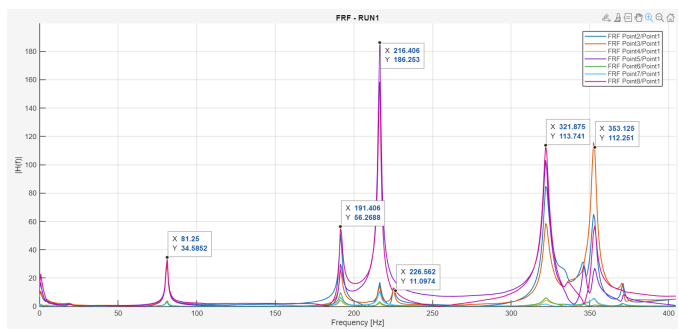

Fig. 4. Spectrum obtained from the piezolectric instrumentation.

After completing this first testing phase, the experiment was repeated by acquiring data from the FBG sensors. As can be observed in Fig. 5, the high sensitivity of the gratings makes even the relatively small mechanical impacts characteristic of hammer tests clearly detectable.

Following the post-processing procedure applied to the fiber data, described in Section II, it was possible to compute the natural frequencies of the system using the FBG measurements. The FFT results are reported in Fig. 6, while the corresponding numerical values are summarized in Table III.

Table III schematically reports the natural frequencies obtained using the accelerometers, those calculated using the FBG sensors, and the percentage error between the two measurements. The results show that below 300 Hz the correlation between the two measurement systems is excellent, with an error level equal to or lower than 2%. At higher frequencies, a filtering effect induced by the Kapton adhesive layer begins to become noticeable.

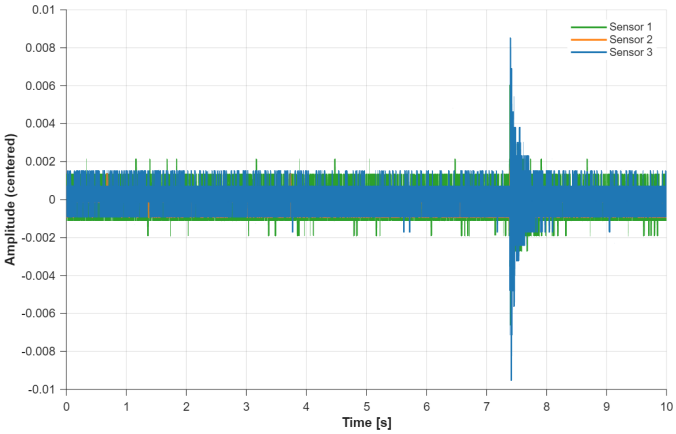

Fig. 5. Example of FBG raw data during an Hammer test.

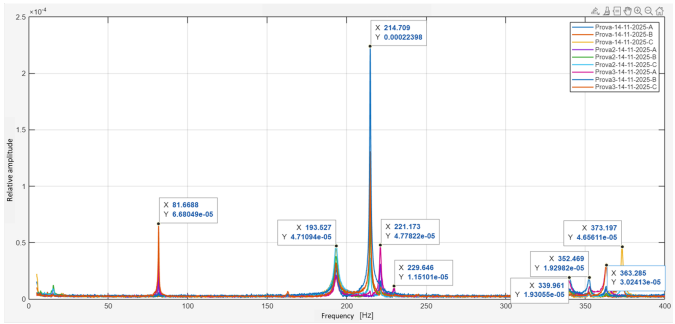

Fig. 6. Spectrum obtained from the FBG .

A particularly interesting aspect is that the optical fibers were able to detect the fifth vibration mode, which could not be identified using the accelerometer measurements but existing in the numerical simulation.

IV. Conclusions

This work investigated the feasibility of using Fiber Bragg Grating (FBG) sensors for the experimental identification of the natural frequencies of a composite plate through an impact hammer test. The obtained results were compared with those measured using a traditional accelerometer-based measurement system in order to assess the reliability of the proposed optical sensing approach. The experimental results showed an excellent agreement between the frequencies identified using FBG sensors and those obtained with accelerometers. In particular, for frequencies below 300 Hz, the discrepancy between the two measurement techniques remained within approximately 2%, demonstrating that FBG sensors are capable of accurately capturing the dynamic response of the structure. The results also highlighted the high sensitivity of the optical gratings, which allowed the detection of vibration modes that were not clearly identifiable using the reference accelerometric system. Another important outcome of the study concerns the practical applicability of the sensing approach. The experiments demonstrated that reliable measurements can be obtained even when the optical fiber is simply fixed to the structural surface using industrial adhesive tape (Kapton). This result validates the possibility of implementing FBG sensors in a plug-and-play configuration, significantly simplifying installation procedures and reducing the complexity typically associated with embedded sensing systems. These findings open interesting perspectives for the development of intelligent composite structures equipped with integrated optical sensing networks. Such systems could enable real-time monitoring of structural vibrations, allowing the continuous comparison between the measured dynamic response and the expected natural frequencies of the structure. Deviations from the nominal modal behavior could therefore be used as indicators of structural degradation or damage. Finally, the proposed approach could be extended beyond the simple identification of natural frequencies toward a more comprehensive modal analysis, including the monitoring of vibration mode shapes. This capability would further enhance the potential of FBG-based sensing systems for structural health monitoring applications in advanced aerospace composite structures.

Table III
Natural Frequencies Obtained From FBG Sensors

Mode n.	Frequency [Hz]
1	81.6688
2	193.527
3	214.709
4	221.173
5	229.646
6	339.961
7	352.469

Table III
Comparison between the peak frequencies measured in the two methods

FBG Frequency [Hz]	Accel. Frequency [Hz]	Error [%]
81.6688	81.2500	0.515
193.527	191.406	1.108
214.709	216.406	0.784
221.173	-	-
229.646	226.562	1.361
339.961	321.875	5.619
352.469	353.125	0.186

V. Acknowledgement

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