Innovative: International Multi-disciplinary Journal of Applied Technology
(ISSN 2995-486X) VOLUME 02 ISSUE 07, 2024

Development of Adaptive Composites for Vibration Monitoring and Active Damping using Embedded Optical Fiber and Piezoelectric Ceramics Preparation

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Abstract:

This study aims to develop composite materials capable of monitoring vibrations and actively damping them. These materials comprise an external Fabry-Perot interferometer with low-fiber optical fibers for measuring vibrations and piezoelectric ceramics for active damping. The study specifically focuses on the process of developing monitoring processes.

The study demonstrates that the proposed external Fabry-Perot transducer interrogation technique was effective in monitoring composite material panels during dynamic bending tests with the diode system at varying frequencies. The inclusion of both sensing and control components, such as optical fibers and piezoelectric ceramics, within layers of composite materials reinforced with carbon fibers was discussed. For the active component, the efficiency of the embedding process was evaluated based on the ability of the piezoelectric ceramic to measure dynamic stress changes of the composite materials using the inverse piezoelectric (PZT) effect.

Keywords: Composable smart materials, piezoelectric, health surveillance, Fabry-Perot interferometer.

Introduction

Advanced materials research has placed significant and increasing focus on smart composites embedded with sensors during the manufacturing process. The main challenge in this field is ensuring the integration and effective monitoring of sensors after embedding, especially when the composite is exposed to specific procedures [1]. Fiber optic sensors and piezoelectric sensors are two common types of sensors used in smart vehicle applications due to their unique properties [2].

Fiber optic sensors, such as those based on the external Fabry-Pérot interferometer (EFPI) design, have gained popularity due to their reduced dimensions, which make them less intrusive in composite materials. They offer pressure and acoustic emission measurement capabilities which makes them ideal for monitoring the integrity of composite materials [3]. However, their fragility at access points can limit their industrial use but on the other hand piezoelectric sensors, especially lead zirconite (PZT) ceramics, provide high pressure sensitivity and fast response times, making them valuable for damage detection in smart composite structures through... Vibration [2, 3, 4]. However, the larger dimensions and connectivity issues in carbon fiber reinforced composites present challenges [4].

Recent advances in printed circuit board (PCB) technology provide a solution for minimally invasive piezo-ceramic integration [4, 5]. In order to circumvent these challenges, in this study we propose a hybrid vibration monitoring and control system using both an EFPI fiber optic sensor for high vibration measurements. Accuracy and PZT ceramic sensor for operating characteristics [6].

We describe the process of embedding these sensors and actuators into carbon fiber/epoxy laminates and evaluate their effectiveness based on their ability to efficiently detect dynamic strains in the composite after embedding [7]. Our approach bridges the gap between fiber-optic sensors and piezoelectric sensors, taking advantage of their unique capabilities.

Research mythology:

The Fabry-Pérot External Interferometer (EFPI) sensor is the best device for detecting plant diseases as it relies on the interference of two magnetic ELEC waves. As for the components of the device, the device consists of two parallel mirrors separated by a distance L, where the two mirrors of the device are arranged so that the wavelengths in the direction of propagation of the light wave are in the same plane. As for the optical fibers, they operate with single mode ends and a reflection rate of 4% at the air/silica interface as reflective surfaces. In order to ensure the balance of the mirrors, a silica capillary is used, and the EFPI device produces an approximate interference pattern when illuminated with broad light.

It is necessary to perform a demodulation process to determine the phase shifts resulting from the deformation of the material to obtain accurate results, since the signal obtained from the device is a direct value of the wave movement, where the action is within the linear region of the response curve, and the relationship between the phase shift and the reflected intensity is linear. (When squared) we therefore find an increase in the change in reflected intensity by determining the optical phase of the wave, as the EFPI sensor is of low quality and does not provide a final result, so the demodulation process is necessary to extract valuable information from the interference pattern .[8]

The demodulation process is considered the basic and most important process in order to extract accurate information from the sinusoidal interference pattern resulting from the EFPI device when exposed to broad light. This is done by adjusting the device so that its reaction is linear in the linear region of carbon. The device is evaluated by the efficiency of the embedding process based on the ability of piezoelectric ceramics to measure dynamic stress changes in composite materials using the reverse piezoelectric effect (PZT) [9]. The device is also distinguished by its accuracy in monitoring minute phase transitions as a result of distortions in the material, which contributes to its use in areas such as disease monitoring. Plants, as it can identify changes in the structure of plants and enhance interaction with crops and the environment. The EFPI device represents an innovative technology that combines optical and piezoelectric techniques to monitor and analyze dynamic changes in materials, which makes it useful in multiple applications that require high precision in measurements and monitoring

$$\delta = \tan^{-1} \frac{v2-V2}{v1-V1} \qquad (1)$$

He is also developing a fiber-optical sensing system for measuring static pressure, using a Fabry-Pérot interferometer (EFPI) as well as fiber Bragg gratings (FBGs). The EFPI device is based on the interference of two electromagnetic waves with a 90 degree phase difference, which greatly enhances the sensitivity of the readings. This phase difference was obtained by selecting two narrow spectral bands from a broadband optical source illuminated by EDFA using two FBGs with a quadratic phase relationship [9]. These signals were then converted into electrical signals through photodetectors and the phase difference, which is linearly related to the EFPI cavity length, was measured to determine the strain used [Equation (1) and Equation (3)]. For dynamic pressure measurements, the cavity length need not be measured from the optical spectrum analyzer but from the phase contrast [Equation (4)].

$$L = \frac{(m\lambda 3\ \lambda 4)}{2(\lambda 4 - \lambda 3)} \qquad (2)$$

$$\varepsilon = \frac{\Delta L}{D} \qquad (3)$$

A piezoelectric ceramic (PX5-N from Morgan Electronics) is used as the actuator and is sandwiched between two layers of CFRP fibers. To address the challenges of electrical insulation during fusion bonding, insulating films and high-temperature wires have been used to prevent short-circuiting[10]. The insulating film was necessary to protect the anode and cathode from contact with the carbon fiber and the integrity and functionality of the PZT element had to be verified using resistance measurements and ESPI observations after inclusion [Material properties of the PZT] and then applied voltages ranging from 5V to 100V in order to determine the maximum For displacement of the laminate plate. Until finding a linear relationship between the operating displacement and the input voltage, then determining the surface displacement factor for the voltage applied to this thin plate[11].

$$L = \frac{\Delta\delta}{4\,\pi\left(\frac{1}{\lambda 1} - \frac{1}{\lambda 2}\right)} \qquad (4)$$

The researchers are also working on fabricating thick composite panels using carbon/epoxy prepreg materials with integrated PZT actuators and EFPI sensors for dynamic strain measurements. The composite panels have dimensions of 200 x 50 x 1 mm and consist of two layers of woven carbon/epoxy prepreg materials and four intermediate layers of One-way carbon/epoxy prepreg materials. The sensor and actuator are listed in the middle layer [12].

Regarding dynamic tests, the composite plate must be subjected to four-point bends under different frequencies (10-100 Hz with 30 Hz intervals) and the respective displacement lengths at the center of the sample recorded using the Spider 8 acquisition system from HBM at a 1 kHz sampling rate in order to evaluate the integrity. The quality of embedding of the sensors was achieved by analyzing their pressure responses, which included an electrical pressure gauge attached to the surface of the plate[13]. Then record and compare the PZT, strain gauge and EFPI signals and the relationship between the recorded voltage signal and the stress of the EFPI sensor can be found using equations 1, 3 and 4.

Temporal responses of 70 Hz demand for the PZT sensor and EFPI sensor demonstrating similar reliability for strains must be achieved to account for a constant response amplitude up to 100 Hz. To measure dynamic strain, BraggSCOPE is used, a commercially available high-speed FBG interrogator that features a wideband optical source. And optical filtration technology [14].

Result and Discussion:

The use of a low-resolution external Fabry-Perot interferometer (EFPI) sensor has yielded important insights into material deformation and phase transformations. The performance of the EFPI sensor, which is characterized by a quasi-sinusoidal output signal, is shown in Figures 2 and 3, which show the spectral response and transfer function curve, respectively. Regarding the spectral response of the EFPI sensor, it showed a quasi-sinusoidal output signal (Figure 2). This signal is necessary to identify the phase shifts caused by Precisely deform the material. Spectral response indicates that the sensor is operating effectively within its designed parameters.

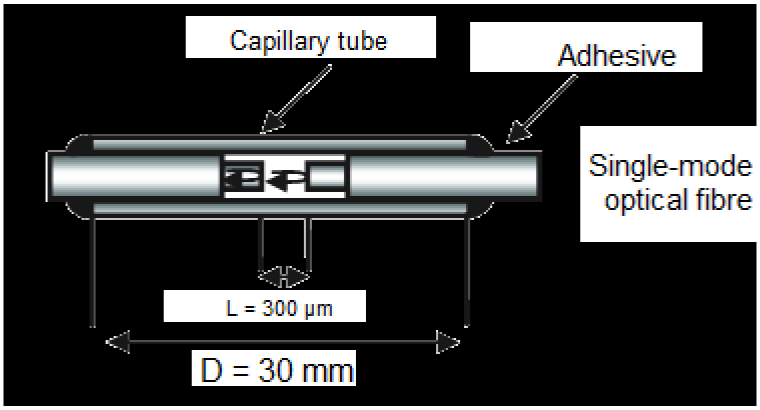

Figure 1. EFPI low-quality optical fiber Sensor.

Regarding the transfer function curve, the transfer function curve (Figure 3) for the EFPI sensor revealed that the relationship between the phase shift and the reflected intensity remains constant at the square point. Operating at this point increases the sensitivity of the sensor to the maximum, making it very effective in detecting subtle phase shifts due to distortion. Subject[15].

Regarding demodulation requirements, since the EFPI sensor does not provide wave displacement values directly, demodulation is necessary to obtain final results, as the spectral response (Figure 2) and the transfer function curve (Figure 3) indicate that operation is within the linear response region, between peaks and valleys. It provides the most significant change in reflected intensity for a given phase shift of light[16].

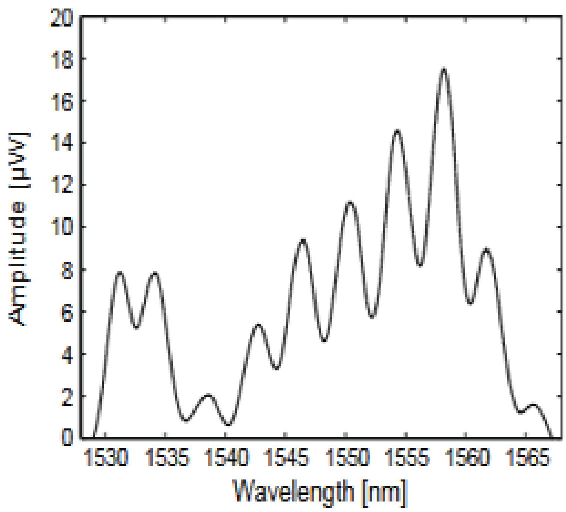

Figure 2. Spectroscopic response of EFPI

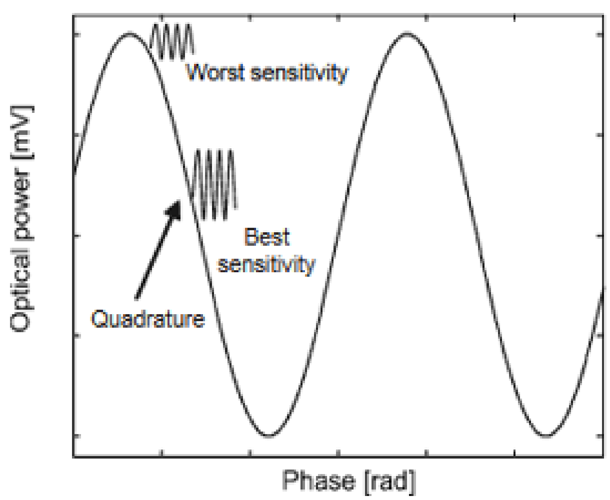

Figure 3. Transfer function curve for EFPI sensor.

With regard to sensitivity and accuracy, this study shows that the sensitivity of the EFPI sensor reaches its maximum when operating at the square point. The result of this study combines with the theoretical expectations of several other studies and highlights the importance of precise alignment and stability of the interferometry system, as it was shown that the use of frequency and phase modifiers with a group Piezoelectric elements are capable of achieving active stability while being able to maintain the accuracy and reliability of the sensor.

The EFPI sensor has the ability to detect subtle phase transitions, which makes it a distinctive sensor for many applications that require accurate measurement of material deformation, including structural health monitoring, where early detection of deformation can prevent catastrophic failure within important environments within various engineering applications where material integrity is important. In comparison with traditional sensors, the EFPI sensor is based primarily on the optical point principle in linear response environments with a response curve with distinct advantages. The quasi-sinusoidal output signal provides a clear and interpretable response, which facilitates accurate measurements even in difficult environments [17].

Figure 4 shows the experimental setup for EFPI interrogation, with an emphasis on the stability and phase recovery needed for accurate measurements. Shows the complete setup for EFPI sensor interrogation. This setup uses biphasic signals that are 90° out of phase to enhance the sensitivity and stability of interferometer readings.

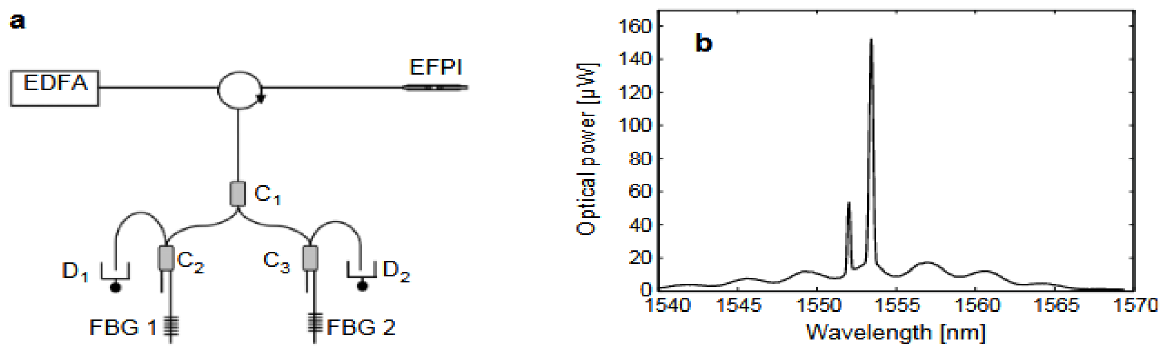

Figure. 4. Experimental setup for EFPI interrogation (a) and wavelength spectrum of light reflected by two FBG (b)

For fiber optic networks (FBGs) the setup uses FBGs to select specific spectral frequency bands when illuminated by a wideband optical source, such as an erbium doped fiber amplifier (EDFA). This allows phase recovery by obtaining two signals in quadrature, which is critical for accurate phase measurement. For optical spectrum analysis, Figure 4b shows the optical power spectrum measured at C1 after reflection by both ends of the FBG. The narrow bands of light reflected by the FBGs (shown as peaks in Figure 4b) are converted into electrical signals using JDS Uniphase photodetectors with a bandwidth of 100 kHz (D1 and D2).

- The reflected light intensity is then used to determine the phase δ through equation (1), where $(V_{\{1,2\}})$ are the constant voltages depending on the optical power and gain of the detection electronics, and (v_{1}) and (v_2) These are the voltages generated by the optical detectors[18].

For Bragg Wavelength and Phase Quadrature Bragg wavelengths are carefully selected to ensure phase quadrature, which operates within a linear response curve, enhancing the sensitivity of the EFPI sensor. The phase δ is proportional to the cavity length L of the EFPI, allowing accurate stress measurement.

Calculate the strain where the strain is derived from the phase \(\delta\) and the cavity length (L). The cavity length is determined by counting the number of cilia over a specific wavelength range, ensuring accurate pressure measurement. To measure dynamic strain, the cavity length(L). is derived from the phase change through equation (4).

- The wavelengths (λ_{1}) and (λ_{2}) are chosen to achieve the desired phase contrast, ensuring the accuracy of dynamic stress measurements. The actuator chosen is a piezoelectric ceramic PX5-N (Morgan Electronics), measuring 12×12×0.3 mm³, and polarized perpendicular to the electrode planes. Engine characteristics are listed in Table 1.

Table 1. Material characteristics of PZT.

Parameters	Values
Intensity	$7.90\ \frac{g}{cm^3}$
Poisson ratio	0.29
The charge constant is d31	$-189\times10^{-12}\ \frac{m}{V}$
The charge constant is d33	$442\times10^{-12}\ \frac{m}{V}$
Constant Voltage G31	$24\times10^{-3}\ \frac{m}{V}$
Constant Voltage G33	$-11.3\times10^{-3}\ \frac{m}{V}$
E11 flexible constant	$21.9\ GPa$
Curie temp	325 °C

The PZT actuator is sandwiched between two layers of Seal's CFRP CC206 2/2 twill fabric to develop the embedding action. This setting ensures that the operator can effectively transmit pressure to the EFPI sensor for an accurate measurement.

As for static pressure measurements, it was found that this method is very suitable for static pressure measurements due to the stability and sensitivity of the EFPI sensor system. But it must be known that it is not ideal for the process of measuring vibrations. This is due to the requirements of an optical spectrum analyzer because it is characterized by being very slow for dynamic applications and for the process of variable dynamic stress measurements.

The evaluation of the results showed that the effectiveness of the EFPI sensing system for dynamic pressure measurements in the case of combining the EFPI sensor and the piezoelectric actuator gives a sensitive and reliable solution for measuring dynamic pressure in composite structures. In this case, the system appears to have a high EFPI sensing for many applications, especially for the process of monitoring structural health. For composite materials, the ability to measure both static and dynamic strains with high sensitivity makes it a valuable tool in engineering and materials science. The low-resolution EFPI sensor, combined with a piezoelectric actuator, provides a powerful solution for measuring dynamic strain in composite structures. The experimental setup, characterized by its high sensitivity and reliable phase recovery, provides accurate pressure measurements, which are essential for various practical applications in structural health monitoring and material analysis [19].

The process of incorporating PZT (Piezoelectric Transducer) ceramic into CFRP (Carbon Fiber Reinforced Polymer) composite involves several steps where careful handling of the dielectric is required to prevent short circuits during the curing process. The procedure for embedding PZT ceramics in the middle layers of CFRP sheets includes:

1. High temperature wire welding with PZT ceramic, using insulating materials to prevent contact between anode and cathode PZT and carbon fiber.
2. A 0.39 mm thick buffer layer is added to further isolate the PZT ceramic from the carbon substructure.

3. Vacuum packing and placing the plates in an autoclave for processing.
4. The curing cycle includes the following stages: heating ramp at 4°C/min, 1-h holding at 123°C, well below the PZT Curie temperature, followed by cooling at 1.4°C/min. A pressure of 0.1 N/mm² and an internal vacuum of 0.085 N/mm² are applied.

Integrating PZT sensors into composite materials often involves dealing with electrical insulation concerns. During the autoclave phase, PZT ceramics can be vulnerable to short circuiting. To address this issue, insulating films are used to keep the PZT anode and cathode separate from the carbon fiber during the curing process. The integrity of the PZT component is tested qualitatively through resistivity measurements and quantitatively through electron speckle pattern interferometry (ESPI) observations [14]. During the application of voltages ranging from 5V to 100V, the sample is rigidly fixed at one end. As a result, the actuator displacement causes a flexural displacement in the rigid body, with the maximum anisotropy in the shape of the lamellae being considered as an induced displacement. The linear relationship between the applied voltage and the operating offset of the low input voltage is determined. The conversion factor between surface displacement and applied voltage is 0.062 μm/V for the given thin plate[20].

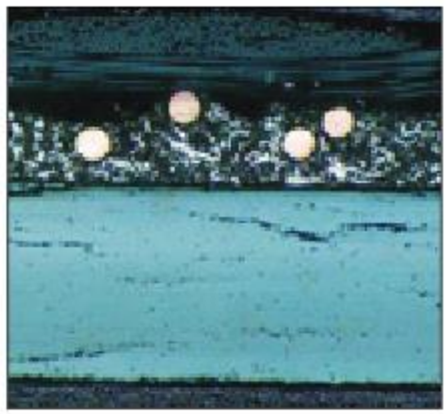

Figure 5. Microstructural observation of embedded PZT.

To evaluate the effectiveness of the fiber optic system in measuring dynamic stresses, dynamic tests were performed on a composite panel subjected to a quadruple point bending test at varying frequencies ranging from 10 Hz to 100 Hz, in 30 Hz increments. These tests were carried out using a maximum frequency mechanical tester. The maximum slip was determined to be 2 mm, which was at the center of the sample length. The integration of sensing and control elements was evaluated, as well as the success of their effective embedding in the composite material through their capabilities to sense dynamic stresses accurately and efficiently.

An electrical strain gage was attached to the plate's surface to verify the dependability of both the EFPI and PZT responses. Simultaneous recordings of PZT, electrical strain gage, and EFPI signals were captured using the Spider 8 acquisition system from HBM at a frequency of 1 kHz. The readings for the voltages of the PZT and EFPI are provided in volts. Since the PZT element factor, being the relationship between strain and voltage, varies depending on the host material and is different after embedding, it can be determined using ESPI [14 - 16]. The strain-voltage relationship for the EFPI sensor can be derived from equations (1), (3), and (4). In Figures 7 and 8, the time responses during approximately 0.14 seconds for a 70 Hz loading frequency are demonstrated for both the PZT element and EFPI sensor.

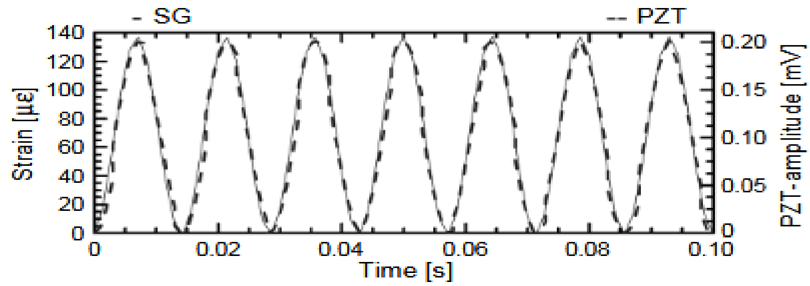

Figure 7. Relationship between the PZT response and the composite longitudinal strain at 75 Hz.

Both the PZT and EFPI exhibited comparable reliability at a frequency of 70 Hz, as shown in Figures 7 and 8. The amplitude of their responses remained constant for frequencies up to 100 Hz (Figure 9). Thus, it can be concluded that the sensing and actuating elements were effectively embedded in the composite material.

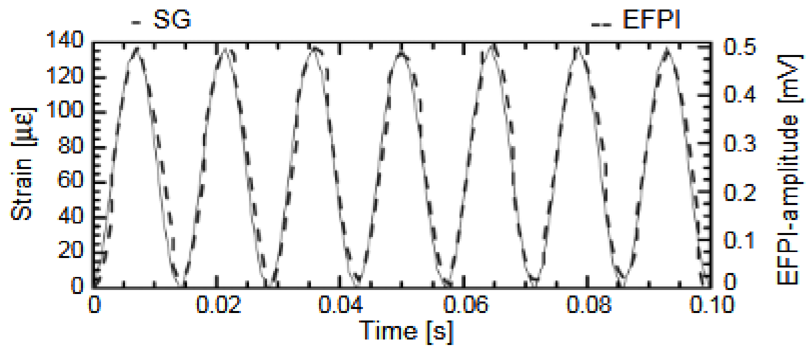

Fig. 8. Relationship between the EFPI response and the compound longitudinal strain at 75 Hz.

The fiber optic system presented in this study was successful in achieving dynamic strain measurement [21]. Another fiber optic sensor known as Fiber Bragg Grate (FBG) was considered for the same purpose. The FBG was embedded in a composite panel with identical dimensions and subjected to identical testing conditions. A high-speed FBG interrogator BraggSCOPE, of fiber sensing (SA) using a wide-band optical source and advanced optical filtering technology was used to monitor the dynamic pressure at different frequencies. However, the use of FBGs to measure strain at these frequencies poses challenges mainly due to the necessity of correlating strain values with optical energy differences that appear as wavelength shifts [22–23].

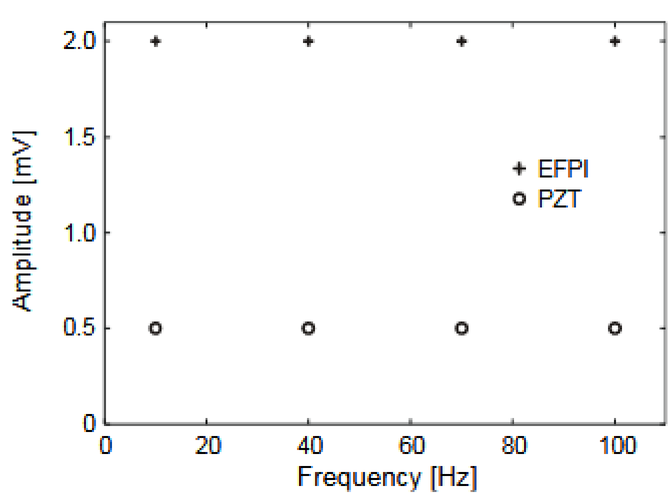

Figure: 9. Variation of sensor response amplitude vs. solicitation frequency

The results highlighted that the proposed interrogation method for the low-resolution EFPI sensor proved to be more reliable for high-frequency strain measurements compared to FBG sensors interrogated using BraggSCOPE. The EFPI sensors, which take advantage of the interference of electromagnetic waves with a 90-degree phase difference, provided direct, sensitive measurement of pressure through changes in interference patterns, ensuring accurate and consistent readings even at higher frequencies. This is in contrast to FBGs, where pressure interpretation is based on complex wavelength measurements influenced by environmental factors and sensor placement within the composite structure. the EFPI sensor system emerges as a powerful option for measuring dynamic stress in composite materials, providing enhanced reliability and accuracy over FBG sensors in high-frequency applications.

Conclusions

This study demonstrates that great success has been achieved in developing advanced composite materials that combine low-resolution optical sensors of the EFPI type and piezoelectric sensors/actuators of the PZT type. Through experiments, it was shown that the proposed calibration technique has demonstrated its effectiveness in ensuring the safety of the sensing and control elements. This is for accurate dynamic pressure measurements and high reliability.

The principle of optical sensor fusion (EFPI) was adopted, based on the principle of interference of electromagnetic waves with a phase difference of 90 degrees, until accurate and sensitive measurements of pressure were achieved through changes in the interference pattern. The results gave clear values showing that the values issued by the EFPI device outperform traditional sensors. Like FBGs when used to measure dynamic pressure at high frequencies, it can therefore be said that the EFPI optical sensor has correct readings in terms of consistency and reliability even in difficult environmental conditions. This is evidence that this sensor is an effective tool for monitoring structural health in composite materials.

The study also showed that the piezoelectric PZT-sensor could also be useful in applications requiring active catalysis and sensing. Although the process of embedding PZT elements is complex and needs special care to prevent short circuits during the solidification process, the benefits it provides in catalysis and energy harvesting are promising. Therefore, the possibilities of integration between piezoelectric sensors and optical sensors show promising applications in multiple fields and the experimental results obtained using the EFPI optical sensing system demonstrate the effectiveness of this system in measuring dynamic stress. The combination of the EFPI sensor and the piezoelectric actuator provides a sensitive and reliable solution for measuring dynamic stress in composite structures. The EFPI-sensor system is a powerful option for measuring dynamic stress in composite materials, providing enhanced reliability and accuracy compared to conventional sensors. The study shows that the use of advanced optical sensing systems, such as EFPI, combined with piezoelectric techniques could revolutionize how dynamic stress is measured and the health of composite structures is monitored. These systems offer significant advantages in terms of accuracy and sensitivity, making them valuable tools in the fields of engineering and materials analysis. The ability to measure both static and dynamic stresses with high sensitivity is a major strength, allowing broad applications in structural health monitoring and materials analysis. The development of advanced composite materials integrated with low-resolution EFPI optical sensing systems and piezoelectric sensors/actuators represents an important step towards improving the capabilities of strain measurement and health monitoring of composite structures. Despite the technical challenges associated with including these elements, the significant benefits they provide in improving the precision and sensitivity of measurements make them a promising future investment in the fields of engineering and materials science.

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