Article

Optical Sensing Technology for Capturing Vibrations in the Automotive Industry

Tecnología Sensorial Óptica para Capturar Vibraciones en la Industria Automotriz

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SECIHTI classification:

Area: Engineering
Field: Engineering
Discipline: Mechanical Engineering
Subdiscipline: Automotive Industries

https://doi.org/10.35429/EJT.2025.9.16.4.1.11

History of the article:
Received: June 11, 2025
Accepted: December 10, 2025

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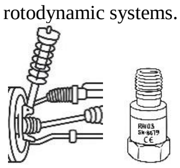
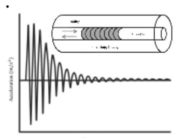
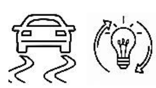
Abstract

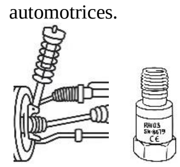
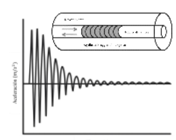
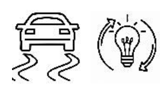
Vibrational analysis in automotive rotodynamic systems faces technical limitations that hinder accurate fault diagnosis. This study proposes the use of fiber optic Bragg grating (FBG) sensors as an advanced alternative to conventional piezoelectric accelerometers, highlighting their electromagnetic immunity and distributed sensing capabilities. An experimental test bench was designed and instrumented with an FBG sensor array, and its functionality was validated through free vibration tests. Results reveal adequate sensitivity of the optical sensors in capturing structural deformations, with damping factor estimates consistent with those from accelerometers. This work constitutes a preliminary step toward comprehensive modal characterization, paving the way for industrial applications in predictive maintenance and structural monitoring.

Objectives	Methodology	Contribution
Evaluate FBG sensors as an alternative to accelerometers for vibrational analysis in automotive rotodynamic systems. 	Test bench instrumented with FBG sensors and accelerometers. Validation through free vibration tests . 	– New technologies applied to the automotive industry – Advances in monitoring and maintenance – Innovation in vehicle stability and safety. 

FBG, Capturing Vibrations, Automotive Industry

Resumen

El análisis vibracional en sistemas rotodinámicos automotrices enfrenta limitaciones técnicas que obstaculizan el diagnóstico preciso de fallas. Este estudio propone la implementación de sensores ópticos de fibra con rejillas de Bragg (FBG) como alternativa avanzada frente a los acelerómetros piezoeléctricos convencionales, destacando su inmunidad electromagnética y capacidad de monitoreo distribuido. Se diseñó e instrumentó un banco de pruebas experimental con un arreglo de sensores FBG, validando su funcionalidad mediante ensayos de vibración libre. Los resultados revelan una adecuada sensibilidad de los sensores ópticos para capturar deformaciones estructurales, con estimaciones del factor de amortiguamiento coherentes respecto a los acelerómetros. Este trabajo representa un primer avance hacia la caracterización modal integral del sistema, abriendo camino a aplicaciones industriales en mantenimiento predictivo y monitoreo estructural.

Objetivos	Metodología	Contribución
Evaluar sensores FBG como alternativa a acelerómetros para el análisis vibracional en sistemas rotodinámicos automotrices. 	Banco de pruebas instrumentado con sensores FBG y acelerómetros. Validación mediante ensayos de vibración libre. 	– Nuevas tecnologías aplicadas a la industria automotriz – Avances en monitoreo y mantenimiento – Innovación en estabilidad vehicular y seguridad. 

Fibra óptica con rejillas de Bragg, Captura de vibraciones, Industria Automotriz

Area: Promotion of frontier research and basic science in all fields of knowledge

Citation: Hernández-González, Josué Iván, Torres-Cedillo, Sergio Guillermo, Hernández-Moreno, Hilario and Cortés-Pérez, Jacinto. [2025]. Optical Sensing Technology for Capturing Vibrations in the Automotive Industry. ECORFAN-Journal Taiwan. 9 [16]1-11: e4916111.

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Article

1. Introduction

Since ancient times, vibrational analysis has been a highly relevant field of study in engineering, serving as a fundamental pillar to ensure the safety and stability of systems [*Au et al.*, 2008]. Such analysis requires the development of advanced measurement instruments that allow for precise evaluation of component performance, enabling timely fault detection and design optimization [T. Li *et al.*, 2017; Xu *et al.*, 2020].

In the automotive field, innovative proposals for the design of mechanical elements increasingly incorporate economic criteria in the optimization of rotodynamic systems. Currently, rotating shafts used in transmission systems and tire assemblies feature lighter and more compact configurations with reduced damping levels, adapting to increasingly restricted structural spaces [Emmanuel Augustine Etukudoh *et al.*, 2024]. During operation, the vehicle chassis serves as the primary medium for transmitting vibrations to the bodywork, originating from both the engine and the tire-surface interaction [Lim & Singh, 1991]. These vibrations pose a technological challenge for the automotive industry, which seeks to minimize their propagation to enhance user comfort and reduce maintenance costs simultaneously.

In this context, controlling vibration levels in rotating systems becomes essential, as phenomena such as imbalance and misalignment not only compromise the useful life of components but also vehicle safety as a whole [Hossain *et al.*, 2024]. Poor control of these conditions can lead to instability during driving and, in extreme cases, to fatal accidents.

Therefore, the study of the dynamic behavior of rotodynamic systems represents a growing interest both in academia and in the generation of practical solutions for the automotive industry, particularly in the design of new predictive maintenance schemes [Jazar, 2008].

Figure 1 illustrates the configuration of a suspension system, where key elements—such as the constant velocity joint and the steering knuckle—are affected by vibratory phenomena that induce misalignment and premature wear.

Among the most common indicators of wheel imbalance are perceptible vibrations in the steering wheel (which intensify with speed), global vibrations in the vehicle body, rear-end skidding sensations during cornering maneuvers, and abnormal tread wear patterns [Ledesma & Shih, 1999]. The causes of such imbalance include various manufacturing defects, improper tire mounting on the rim, irregularities in brake drums or discs, and uneven tire wear [Charles, 1943].

Box 1

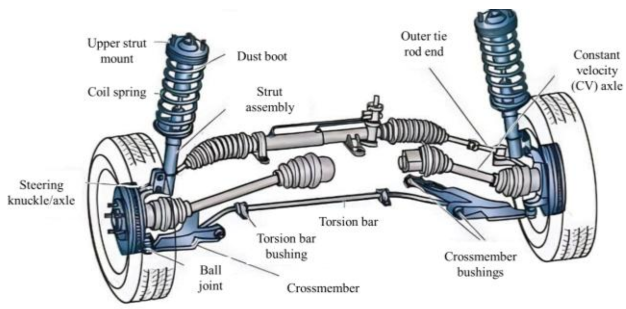

Figure 1
Automotive suspension system.
Source: [Jazar, 2008]

Imbalance in rotodynamic systems has driven the development of a wide range of diagnostic techniques, among which modal balancing and influence coefficient methods stand out [Jazar, 2008]. However, both approaches require the installation of trial masses and sensors directly on the rotor, which limits their applicability under real operating conditions due to space constraints and exposure to elevated temperatures [Randall, 2011]. In light of these limitations, the need has arisen to implement non-invasive inverse procedures for imbalance identification. These methods rely on prior knowledge of the chassis's modal parameters and the analysis of vibrational signals captured at the vehicle body to infer the dynamic state of the rotating system [Hossain *et al.*, 2024].

Within this context, an up-and-coming alternative lies in the development of experimental test benches designed to validate methodologies based on nonlinear inverse problems applied to automotive rotordynamics. These test benches serve as practical tools for the precise identification of mechanical faults in rotating systems through indirect diagnostic techniques [Vance *et al.*, 2010; Yang *et al.*, 2017].

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Derived from this need, a representative test bench of a rotodynamic system was designed, capable of operating at speeds of up to 60 Hz. This bench is currently located at the Aragón Technology Center of the National Autonomous University of Mexico, as shown in Figure 2.

Box 2

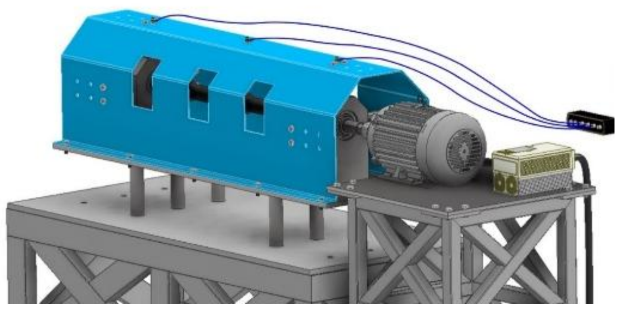

Figure 2
Experimental test bench.
Source: Own Elaboration

As background, the test bench was initially instrumented with piezoelectric accelerometer-type sensors, widely used in experimental rotordynamic analysis studies [T. Li *et al*., 2020]. However, such devices present inherent limitations in their operating principle: since they function with low-voltage signals, they are susceptible to environmental disturbances due to electromagnetic fields. This drawback is compounded by the requirement for complex cabling and electrical connections [T. Li *et al*., 2020; Xiong *et al*., 2021].

In light of these limitations, an alternative was identified in the implementation of fiber optic sensors based on Fiber Bragg Gratings (FBG), which have garnered increasing interest due to their high sensitivity, compact dimensions, and immunity to electromagnetic interference by virtue of utilizing light energy for operation [Hernández-Moreno *et al*., 2009b; Kim *et al*., 2022; K. Li *et al*., 2014]. Their operating principle, based on wavelength modulation, enables their installation at multiple sensing points along a single fiber, allowing for analysis through wavelength-division multiplexing interrogation techniques. This approach not only expands monitoring capabilities but also optimizes the efficiency of the measurement system by requiring only a single light source and a unique detection unit, thereby significantly reducing costs associated with the use of such instruments, known as optical interrogators [García *et al*., 2010; Hernández-Moreno *et al*., 2009a].

2. Theoretical Framework

Through a contemporary literature review based on primary sources, two particularly relevant approaches for the implementation of FBG sensors in dynamic applications have been identified. The first corresponds to the development of optical accelerometer-type sensors, as illustrated in Figure 3, whose operating principle is based on wavelength displacement. The second focuses on the construction of experimental setups specifically designed for the monitoring of engineering systems, as shown in Figure 4 [Hernández-González *et al*., 2023].

Box 3

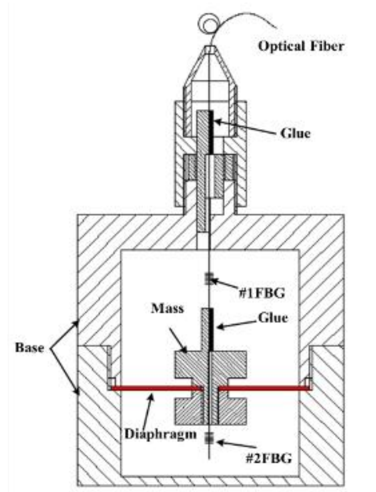

Figure 3
Optical accelerometer-type sensor.
Source [T. Li et al., 2017]

Box 4

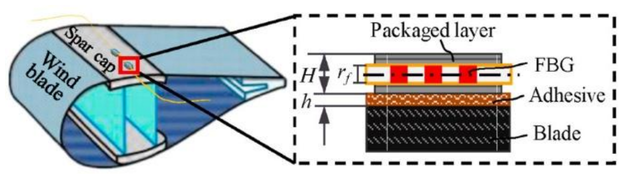

Figure 4
Experimental setup of FBG sensors.
Source [Javdani et al., 2016]

The essential distinction between the two application approaches lies in the number and distribution of analysis points. While an optical accelerometer-type sensor serves as a substitute for a conventional accelerometer, limiting its measurement to a specific point, experimental setups permit the installation of multiple sensors along a single fiber, thereby enabling the distributed characterization of the system under study.

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Thus, due to the sensitive characteristics of Bragg gratings, any variation on the monitored surface—whether in terms of strain, temperature, or hydrostatic pressure—is directly reflected in the grating through a change in wavelength [García *et al*., 2010; Kim *et al.*, 2022].

The development of optical accelerometers remains an active field of innovation, aimed at improving sensitivity and design through adjustments in materials and geometries [K. Li *et al*., 2014]. In parallel, FBG experimental arrays are consolidating as a promising alternative for structural monitoring, as they allow distributed detection with minimal impact on the mechanical integrity of the structure since they can be adhered or integrated into the material [T. Li *et al.*, 2020]. Both approaches present advantages and limitations: optical accelerometers stand out for their versatility, while arrays offer a more comprehensive view, though requiring high precision in their installation.

In recent years, interest in FBG arrays has grown significantly, driven by advances in interrogation systems for monitoring, which has expanded their applicability in dynamic studies [Tozzetti *et al*., 2021]. Consequently, the choice between the two strategies must be based on the nature of the system and on technical, economic, and experimental feasibility criteria.

3. Experimental Design

Once the theoretical foundation was established, experimental design required determining the most suitable strategy for the implementation of FBG sensors. In this study, an experimental array of three sensors adhered to the surface of the test bench casing was chosen, based on the premise that phenomena occurring in the rotational shaft are transmitted through the bearings to the casing. This decision responds to the need for multiple analysis points in the bearing support zones—front, middle, and rear—recognized in the literature as critical positions for rotodynamic evaluation [Hou & Cao, 2019; Torres Cedillo & Bonello, 2016].

Although FBG-based optical accelerometers represent an up-and-coming alternative in vibrational contexts, their development entails significant investment of time and resources, in addition to being limited to instrumentation at a single point per sensor.

In contrast, arrays take advantage of the multiplexing capability of FBGs, facilitating simultaneous coverage of several points with a single optical interrogator. In this case, the choice was supported by the operational characteristics of the test bench, which reaches a speed of 60 Hz, and the availability of a si425 optical interrogator with a 250 Hz bandwidth, sufficient under the Nyquist-Shannon theorem for obtaining efficient data under dynamic conditions [Hernández-González *et al*., 2023; Preizler *et al*., 2017]. Thus, the array proposal responds not only to technical and economic efficiency but also to the experimental relevance of adapting FBG technology to the real context of the study.

Subsequently, the formal design of the FBG sensor array was carried out, which required defining both the materials and dimensions for experimental applications. The result was a design consisting of single-mode optical fiber coated with acrylate and polyamide, FC-APC connector, and three Bragg gratings with a physical length of 10 mm, staggered in 5 nm intervals (1535 nm, 1540 nm, and 1545 nm).

This configuration addresses the need to instrument critical areas of the test bench—both support bearings and the intermediate region between them. Due to the technological complexity involved in the manufacture of FBG arrays, particularly the precise inscription of gratings in the fiber, production was delegated to a specialized company capable of ensuring optical parameters such as reflectivity above 80%, a bandwidth of 0.20 nm, and a signal-to-noise ratio greater than 15 dB.

The installation process was carried out with maximum precision criteria, ensuring at all times the structural and functional integrity of the sensors during their installation. Figure 5 shows a top view of the experimental test bench, where the optical fiber sensor array was carefully integrated into the surface using epoxy adhesive.

To reinforce its protection, fiber sections not covered by gratings were coated with a transparent PVC layer, which also allowed the use of adhesive clips to limit axial displacement of the fiber without the need to perforate the test bench casing.

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Box 5

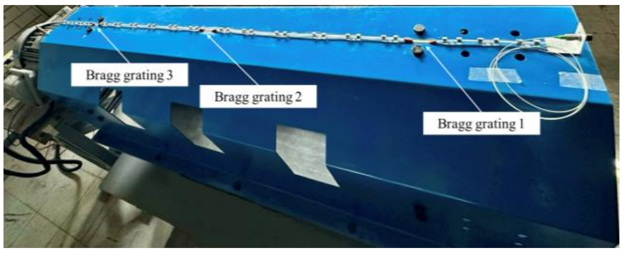

Figure 5
Optical fiber with Bragg gratings installed on an experimental test bench.
Source: Own Elaboration

4. Experimental Study

4.1 Considerations for Rotordynamic Study

In the field of applied rotordynamics, mechanical transmission systems and rolling assemblies in vehicles incorporate components whose vibrational response can be analyzed and understood through simplified configurations. Based on this premise, the developed experimental test bench is conceived as a scaled representation of the actual system, in which the shaft serves as the principal transmission element, the bearings act as supports conditioning the dynamic response, and the motor operates as the source of mechanical excitation [Lim & Singh, 1991].

This reduction to a fundamental shaft–bearing–motor scheme not only facilitates analysis but, from a rotordynamic standpoint, the casing enclosing the test bench preserves the most relevant phenomena associated with the dynamic coupling between the rotating elements and their supports [Lim & Singh, 1992; Vance *et al*., 2010].

Additionally, the experimental bench is capable of analogously emulating half of a rotating shaft in a real transmission system. This approach is justified by the symmetry of vibrational phenomena in longer shafts, whereby studying a representative section is sufficient to extrapolate the overall behavior. Consequently, this experimental simplification does not entail a loss of analytical rigor; rather, it serves as a methodological strategy that enhances the study of rotational dynamics while providing an suitable framework for the validation of analytical and numerical models under controlled conditions [Bugaru & Vasile, 2022; Zingoni, 2014].

4.2 Considerations for Vibrational Study

In this context, free vibration analysis constitutes the essential first stage in the dynamic characterization of a system, as it enables precise identification of natural frequencies and inherent vibration modes before subjecting the structure to external excitation. This procedure provides a reliable reference framework for understanding the intrinsic behavior of the system. It is indispensable for subsequent analysis of forced vibration, in which the motor directly imposes excitation frequency onto the rotating shaft [Feng *et al*., 1998].

It is worth noting that the present work addresses exclusively the introduction to free vibration analysis, to establish the foundation for future, more in-depth investigations that include the study of forced vibration.

Free vibration manifests when a system, after being initially disturbed, oscillates without the action of additional external forces [Beards, 1995]. Its behavior may be classified as stable or unstable: in the former, the presence of positive damping gradually attenuates the oscillation; in the latter, negative damping leads to a self-excitation phenomenon in which amplitude grows progressively until the system's stability is compromised [Lim & Singh, 1991]. In both scenarios, the amplificated vibratory response occurs at one of the natural frequencies of the rotating system, underscoring its close relationship with the fundamental modes of structural dynamics [Matsushita *et al*., 2017].

The parameters that define this behavior—principally the natural frequency and damping ratio—not only allow for the characterization of the vibratory system but also enable the anticipation of resonance scenarios under forced excitation conditions. In particular, the critical speed associated with imbalance-induced vibration is directly related to the shaft's natural frequency, highlighting the importance of precise analysis under free conditions [Matsushita *et al*., 2017].

The transient response generated by a sudden disturbance, such as an impact, constitutes another essential aspect of free vibration analysis.

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This stimulus introduces energy into the system, triggering vibratory motion whose evolution depends solely on the system's intrinsic properties—mass, stiffness, and damping—and not on the magnitude of the impact [Beards, 1996; Szeidl & Kiss, 2020]. for its experimental characterization, techniques such as impact hammer testing are employed, providing a controlled environment for system excitation and enabling the identification of multiple vibration modes.

Through the analysis of the resulting response, it becomes possible to estimate the damping ratio and determine the natural frequencies associated with each mode, delivering essential information for the validation of dynamic models and the prediction of critical operational behaviours [Doebling *et al*., 1996].

4.3 Free Vibration Testing

As a first step, this study aims to establish a correlation between the data provided by FBG sensors and accelerometers, given that the measurements obtained from each technology are inherently not directly equivalent. Due to their sensitivity characteristics, the Bragg gratings installed on the experimental test bench are primarily responsive to strain variations, neglecting effects from temperature and hydrostatic pressure, whereas accelerometers quantify acceleration.

Consequently, a comparative framework is necessary to verify the consistency and reliability of the results obtained from both sensing techniques.

In this regard, the present study seeks to establish an initial quantitative framework concerning the energy dissipation behavior of the system through the damping ratio. However, this preliminary approach does not exhaust the dynamic characterization of the test bench, as the precise identification of the natural frequencies and the corresponding vibration modes remains pending. Such a modal analysis—excluded from this work due to temporal constraints—emerges as an essential step to complement the damping information obtained and to support the validation of FBG sensors in rotordynamic.

Box 6

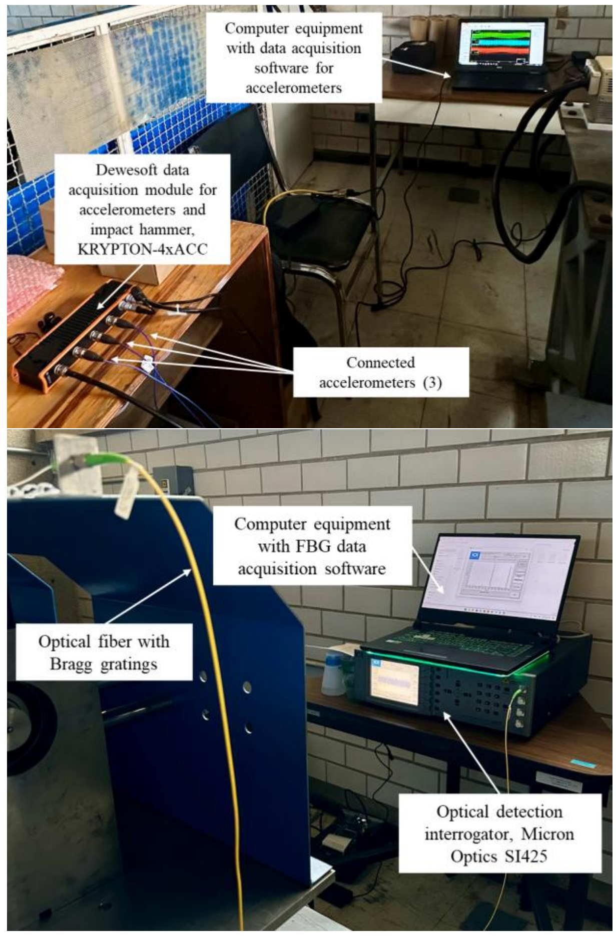

Figure 6

Data acquisition system for experimental testing.

Source: Own Elaboration

To conduct the free vibration study, the monitoring instrumentation depicted in Figure 6 was employed. This setup integrates acquisition devices based on accelerometers and FBG sensors, installed on the outer casing of the test bench. The system includes an optical interrogator model si425, a KRYPTON-4xACC acquisition module responsible for recording both the force exerted by the impact hammer and the accelerometer signals, and dedicated computing systems for data collection.

Although this study does not evaluate reproducibility or impact accuracy, its exploratory approach is valuable in early research stages, allowing the collection of preliminary results to formulate hypotheses, identify limitations, and establish methodological guidelines for future investigations. Practically, each test involved three impacts on the test bench casing near predefined monitoring points (Figure 7), strategically chosen to maximize vibratory response capture in key areas.

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Box 7

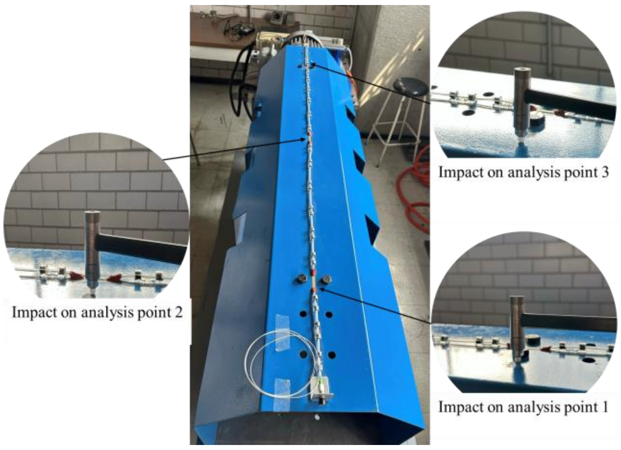

Figure 7
Impact points for free vibration tests.
Source: Own Elaboration

5. Results

As a representative example of the results obtained, Figures 8 and 9 present the experimental records. These include both the force exerted by the impact hammer [N] and the responses of the optical FBG sensors and the accelerometers, expressed in their original acquisition units—wavelength and acceleration, respectively. This test enables a morphological comparison between the responses of both types of sensors to the same dynamic stimulus, offering a reference framework for the comprehensive characterization of free vibration behavior in the system.

Box 8

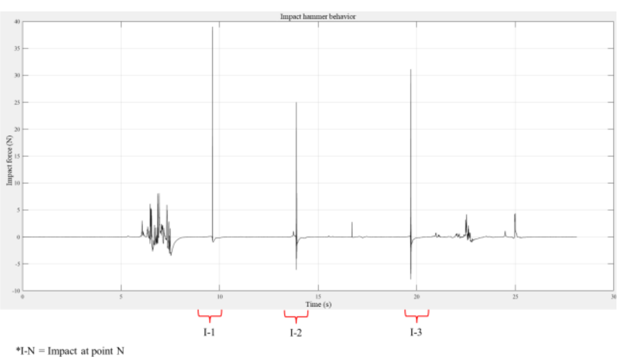

Figure 8
Behavior of the impact hammer.
Source: Own Elaboration

Box 9

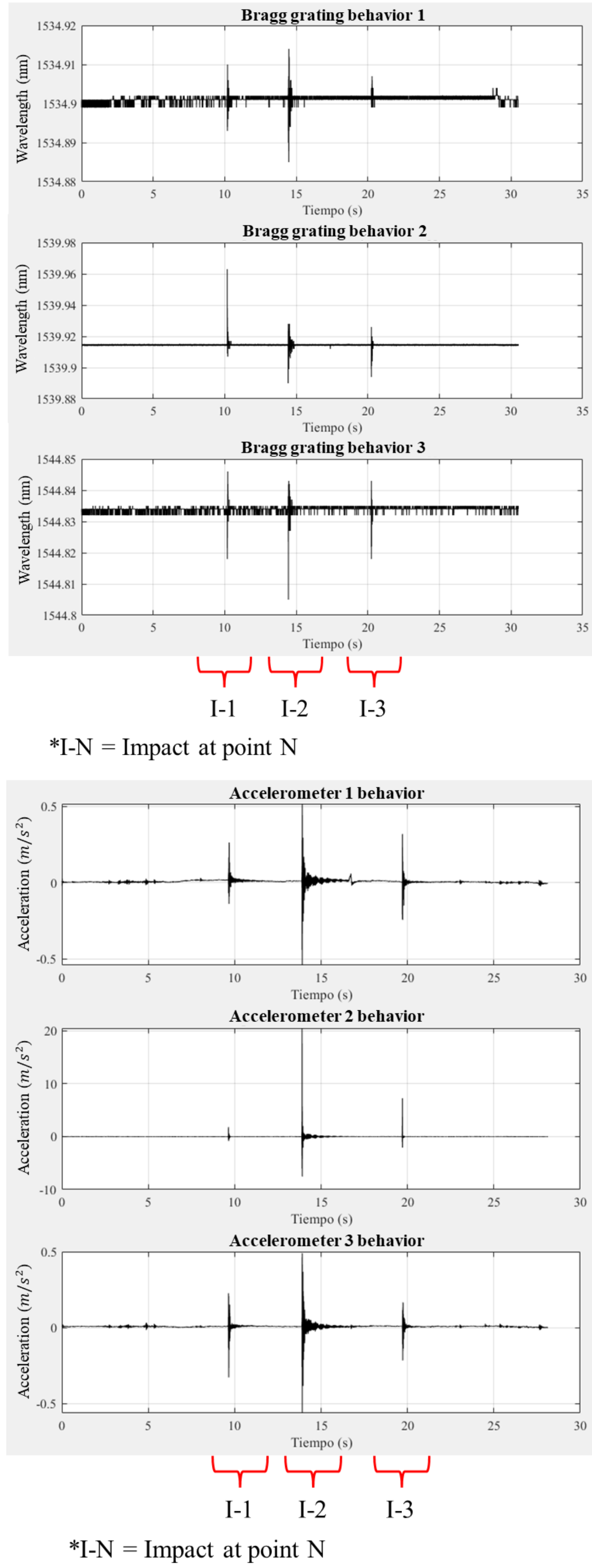

Figure 9
Behavior of the sensors during the free vibration test.
Source: Own Elaboration

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To enhance the analytical approach to the study of FBG, the strain captured by each grating is first determined using Equation 1, which is expressed as a function of the relative wavelength shift $\Delta\lambda_B/\lambda_B$ —where λ_B is the central wavelength of the Bragg grating and $\Delta\lambda_B$ is the wavelength variation induced by mechanical strain—and the photoelastic coefficient of the optical fiber core material, $p_e = 0.219355$ (an estimated value for silica fibers) [Hernández-Moreno *et al*., 2009b].

Thus, for practical purposes in data processing, the responses of the FBG optical sensors and accelerometers will be considered in terms of strain and acceleration, respectively.

$$\varepsilon = \frac{1}{(1-p_e)}\frac{\Delta\lambda_B}{\lambda_B} \quad [1]$$

The data processing applied to the free vibration study was based on the use of the logarithmic decrement and the damping ratio, calculated through Equations 2 and 3 [Matsushita *et al*., 2017]. The former allows the logarithmic decrement δ to be determined from the amplitude ratio a_n over a defined number of complete cycles N_c, while the latter yields the corresponding damping ratio ζ.

$$\delta = \frac{1}{N_c}\ln\left(\frac{a_n}{a_{n+N}}\right) \quad [2]$$

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2+\delta^2}} \quad [3]$$

Based on the impact responses recorded by both the FBG sensors and the accelerometers on the experimental bench, the maximum amplitudes of each signal in the time domain were identified, and the cycles used in the calculation were determined. This made it possible to accurately estimate the logarithmic decrement and, consequently, the damping ratio.

Figure 10 illustrates, as an example, the response of the FBG sensors and accelerometers to an impact applied at point 2 (center) of the test bench, highlighting the initial amplitude (P_{Max}) and final amplitude (P_{Fn}) used in the calculation over a total of 10 cycles.

Box 10

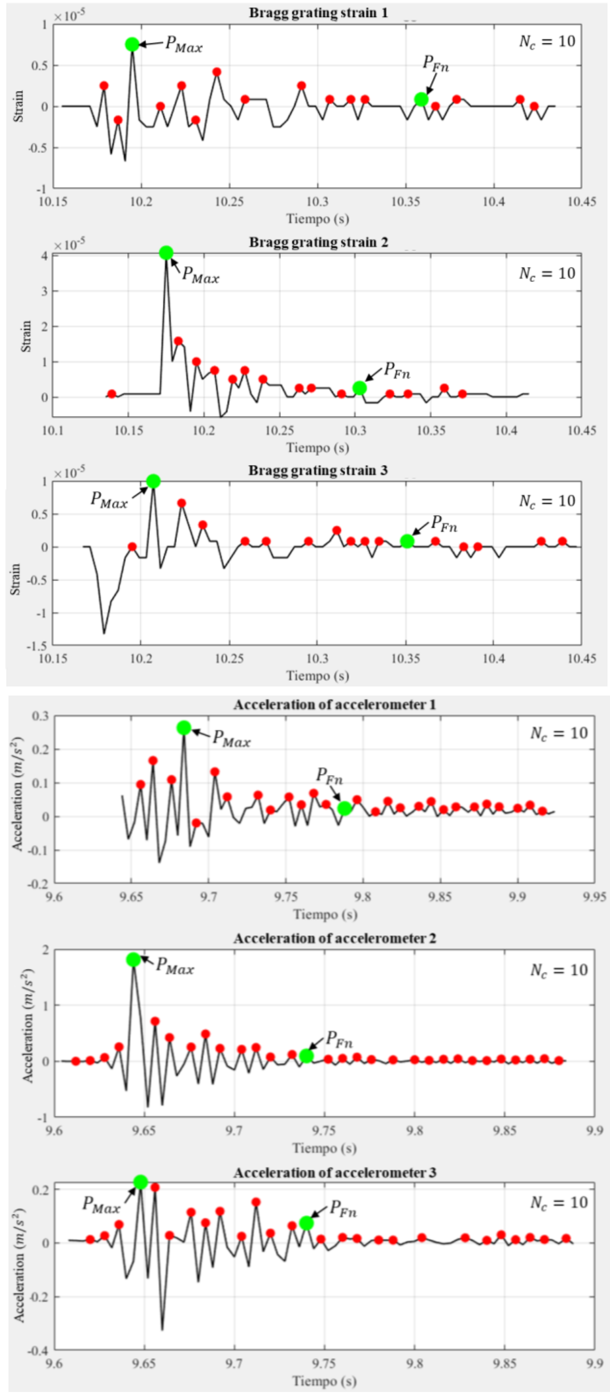

Figure 10
Sensor response at each analysis point.
Source: Own Elaboration

Based on the results obtained from a total of 27 experimental trials—individualized by sensor type and impact location—the equivalent damping ratio for an average force at each analyzed point, along with the corresponding value of the logarithmic decrement, is summarized in Table 1.

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Box 11

Table 1
Equivalent damping factors

Test	Sensor	Average impact force	δ	ζ
Impact on analysis point 1	Bragg grating 1	37.8006	0.2042	0.0325
	Accelerometer 1		0.2981	0.0474
Impact on analysis point 2	Bragg grating 2	34.2359	0.2095	0.0334
	Accelerometer 2		0.4279	0.0679
Impact on analysis point 3	Bragg grating 3	40.1864	0.2119	0.0337
	Accelerometer 3		0.2809	0.0446

Source: Own Elaboration

5.1 Discussion of results

The Bragg grating sensors recorded consistent vibration patterns among themselves, with slight variations in amplitude and frequency attributable to their relative position with respect to the impact point. In contrast, the accelerometers exhibited a more uniform and stable response, likely associated with their higher sensitivity and greater precision in measuring accelerations compared to strain detection. These differences are reflected in the estimation of the damping ratio, as summarized in Table 1.

A more pronounced attenuation was observed in the signals from the Bragg gratings, an effect attributable both to a combination of structural damping factors and to potential interferences resulting from their direct installation on the surface of the test bench. In the comparison between the two sensing systems, the accelerometers systematically reported higher damping ratios at each analysis point.

Globally, the estimated damping ratios confirm that the rotodynamic system under study exhibits low energy dissipation, characteristic of configurations with high stiffness and minimal damping. This behavior is consistent with structures designed to ensure vibratory stability and minimize energy losses per cycle [Beards, 1996].

6. Conclusion

The results confirm that Bragg grating sensors represent a viable alternative for detecting vibrational responses in rotodynamic systems, showing overall agreement with accelerometers, albeit with variations inherent to the nature of each sensing technique.

Nonetheless, the estimation of the damping ratio constitutes only a preliminary step; a precise determination of the natural frequencies associated with the vibration modes of the experimental bench remains pending. This future modal analysis will enable a more comprehensive characterization of structural dynamics. It will consolidate the implementation of FBG sensors as a robust tool in rotodynamic instrumentation, with strong potential for specialized scientific and industrial applications.

Industrial implications include structural health monitoring, performance optimization, and enhanced operational safety. At the same time, in the academic domain, the integration of optical technologies promotes the development of lighter, more compact, and more reliable systems. Furthermore, this technology paves the way toward intelligent diagnostics in predictive maintenance, reinforcing its relevance in sectors such as the automotive industry.

Declarations

Conflict of interest

The authors declare no conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Hernández-Gonzalez, Josué Iván: Contributed to the overall conception of the project, as well as to the methodology, research techniques, experimental development and data analysis.

Torres-Cedillo, Sergio Guillermo: Contributed to the overall conception of the project, experimental development and data analysis.

Hernández-Moreno Hilario: Contributed to the overall conception of the project, the planning of the experimental design, and the analysis of results.

Cortés-Pérez, Jacinto: Contributed to the execution of experimental tests and the experimental setup.

Funding

The research did not receive any funding.

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Acknowledgements

This research was conducted with the support of the "Investigadoras e Investigadores COMECyT 2025" Program. Acknowledgment is also given to DGAPA-PAPIIT through project number IN110923.

Abbreviations

FBG	Fiber Bragg Grating
N	Newtons
nn	Nanometers
nm	Millimeters
dB	Decibels
Hz	Hertz

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Antecedents

Hernández-González, J. I., Torres-Cedillo, S. G., Hernández-Moreno, H., & Cortés-Pérez, J. [2023]. Identification of an instrumental proposal based on fiber optic sensors of the Bragg grating type for implementation in an experimental platform for dynamic analysis. ECORFAN Journal Taiwan, 7–15.

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ISSN: 2524-2121
RENIECYT-SECIHT: 1702902
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