# Identification of an instrumental proposal based on fiber optic sensors of the Bragg grating type for implementation in an experimental platform for dynamic analysis

# Identificación de propuesta instrumental basada en sensores fibra óptica del tipo rejilla de Bragg para implementación en plataforma experimental de análisis dinámicos

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**Abstract**

Recently it has been reported the use of non-invasive methods for the identification and monitoring of vibrational parameters in rotodynamic systems, such as aircraft engines, which require the implementation of innovative detection systems, such as fiber optic sensors, which overcome deficiencies of adaptability to adverse environments such as intense magnetic fields and the impossibility of performing a distributed detection of vibrations, limitations present in the sensors conventionally based on capacitive or piezoelectric principles. Therefore, in the present study, through the use of an experimental platform for dynamic analysis, the best proposal of an instrumental system based on fiber optic sensors with Bragg gratings was selected for its use in vibrational measurement and analysis, through the theoretical study of the different approaches to vibrational analysis using fiber optic sensors with Bragg gratings. The analysis of the results of the study presents a justification of the type of instrumental proposal selected from the characteristics provided by the experimental platform. In addition, the experimental proposal will be implemented in the future and may contribute to the development of other vibrational studies.

**Fiber Bragg Grating (FBG), Vibration monitoring, Instrumental system**

**Resumen**

Recientemente se ha reportado el empleo de métodos no invasivos para la identificación y monitoreo de parámetros vibracionales en sistemas rotodinámicos; tales como los motores de las aeronaves, los cuales requieren de la implementación de innovadores sistemas de detección; como son los sensores de fibra óptica, los cuales subsanan deficiencias de adaptabilidad a entornos adversos como son los campos magnéticos intensos y la imposibilidad de realizar una detección distribuida de las vibraciones, limitaciones presentes en los sensores basados convencionalmente en principios capacitivos o piezoeléctricos. Por lo que, en el presente estudio a través del empleo de una plataforma experimental para análisis dinámicos, se seleccionó la mejor propuesta de sistema instrumental basado en sensores fibra óptica con rejillas de Bragg; para su empleo en medición y análisis vibracional, a través del estudio teórico de los diferentes enfoques que abarcan los análisis vibracionales empleando sensores fibra óptica con rejilla de Bragg. El análisis de resultados del estudio presenta una justificación fundamentada del tipo de propuesta instrumental seleccionada a partir de las características que proporciona la plataforma experimental. Además, la propuesta experimental será implementada en un futuro y puede contribuir al desarrollo de otros estudios vibracionales.

**Fibras con rejillas de Bragg (FBG), Monitoreo vibracional, Sistema instrumental**

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## Introduction

Nowadays, dynamic analysis is highly relevant to ensure the safety and stability of modern engineering systems such as those encompassed in the area of mechanics and civil infrastructure; which require the use of non-destructive measuring instruments for real-time inspection of vibration signals that are important references for dynamic diagnosis, failure prevention and optimization design (Au *et al*., 2008; T. Li, Guo, *et al*., 2020; Xiong *et al*., 2021).

Particularly within the aviation and space industry, vibration not only interferes singularly with the monitoring of aircraft structural integrity, but can also affect other areas such as control and stability systems; and additionally it is not conducive to the physical and mental health of passengers and crew (Fan *et al*., 2011; Kong *et al*., 2022). According to Fan *et al*. (2011), it is of relevance to distinguish that flexible surfaces such as the wing have a high tendency to vibrate and these effects can be transmitted to the fuselage. In this sense, one of the main sources contributing to the presence of vibrations in the case of commercial aircraft, is the propulsion system; which is typically positioned at the bottom of the wing surface (Torres Cedillo *et al.*, 2019).

Recently, it has been reported the use of non-invasive techniques or methods for the identification of failures in rotodynamic systems; such as aircraft engines, where it is not possible to disassemble the rotating elements during their operation, consequently modern monitoring systems are required in order to avoid accidents or economic losses (Torres Cedillo *et al*., 2019).

Based on the above, an experimental platform of reduced size was designed and built, representative of the structure of a rotodynamic system with the capacity to reach an operating speed of up to 3600 RPM (see Figure 1), located at the facilities of the Centro Tecnológico de la Facultad de Estudios Superiores Aragón of the Universidad Nacional Autónoma de México.

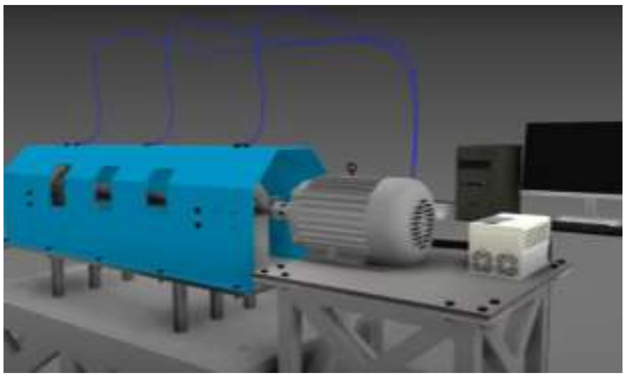

**Figure 1** Experimental platform at scale of the structure of a rotodynamic system
*Author's development*

Currently, the experimental platform presented in Figure 1 is instrumented from the implementation of piezoelectric sensors of the accelerometer type. In this sense, within the experimental bases of dynamic analysis, the implementation of electrical sensors conventionally based on piezoelectric or capacitive principles is generally used, such is the case of accelerometers and strain gauges, respectively (T. Li, Guo, *et al*., 2020). Kong *et al*. (2022), state that the use of strain gauges for the measurement of deformations in the plane of the structure can be used for the estimation of structural vibration parameters such as displacements, rotation angles and angular velocities; which can be part of a complete detection of dynamic vibrations.

On the other hand, accelerometers are a key equipment in vibration measurement and the important role they play. However, both sensors use a weak voltage signal, which daily presents complications for their adaptation in hostile environments as a result of intense magnetic fields, the use of complex wiring joints and the impossibility of a distributed vibration detection, which will limit the long-term monitoring practices and therefore; it is required the implementation of innovative sensors with capabilities to adapt to this type of environment (T. Li, Guo, *et al*., 2020; Xiong *et al*., 2021).

The proposed solution to the problem explained above is the use of fiber optic sensor technology, especially of the Bragg grating type, which has generated interest in recent years in a wide range of applications, including the monitoring of mechanical properties such as strain, temperature, stress, vibration, pressure, force, displacement, directional curvature, among others (Xu *et al*., 2020).

This is due to a number of numerous inherent advantages of which their compact size and light weight, passive sensing capability, operation in harsh environmental conditions, invulnerability to electromagnetic fields, high sensitivity and good corrosion resistance stand out (Chen *et al.,* 2018; Khalid *et al*., 2021; T. Li, Guo*, et al*., 2020).

Added to this, optical sensors based on the principle of operation by wavelength, such as Bragg gratings inscribed in optical fiber present the ability to be installed at multiple detection points using a single fiber, which allows them to be analyzed by multiplexing interrogation techniques by time, frequency or wavelength, which significantly reduces the cost of the measurement system since only one light source and a single detection system are needed, as exposed by Garcia *et al*. (2020). One of the important features specifically in wavelength interrogation is the ability to be unaffected by signal intensity because the strain information is provided, as the name implies, through the wavelength (Hernández-Moreno *et al*., 2009).

As a result of these advantages, fiber optic Bragg grating (FBG) based sensors are excellent solutions for a variety of structural integrity monitoring problems; being able to be inserted into concrete or composite materials, in addition to the ability to perform shape detection, vibration suppression control in complicated civil structures such as bridges or roads and other engineering fields, such as chemical testing and inspection and aggressive environments, including sensors for oil and gas wells and seismic instruments (Garcia et al., 2010; Goossens *et al*., 2021; Kong *et al*., 2022).

## Method

This study seeks to identify the best solution for the construction of an experimental instrumental dynamic monitoring system (conditioned to the use of an optical detection interrogator model si425 from Micron Optics, see Figure 2) to replace the current monitoring system based on accelerometers; The objective is to obtain as a result a solid approach of a monitoring system that adapts to the available resources in terms of economy and available material for the vibrational study of the experimental platform.

**Figure 2** Micron Optics optical detection interrogator model si425. *Luna / Micron Optics SI425-300 Optical Sensing Interrogator (n. f.)*

## Theoretical framework

Fiber optic sensors can be broadly classified into two types of group, extrinsic and intrinsic; the sensors of the first group are distinguished in that the detection is performed in a region outside the fiber, on the other hand; the sensors of the second type present the detection inside the optical fiber itself (Garcia *et al*., 2010). However, fiber optic sensors can also be classified by the principle of operation as described by Garcia *et al*. (2010) in their research and presented below.

Sensors based on light intensity: This kind of sensors present as relevant characteristics a low acquisition cost, a large measurement bandwidth and the possibility of using both reflection and transmission modes (T. Li, Guo, *et al*., 2020). Generally speaking, they can be classified into two categories as mentioned by García *et al*. (2010), depending on whether or not they present physical contact with the vibrating object to be analyzed, in this sense the non-contact structures use a reflective signal to detect vibration, while the other structures use the transmissive configuration.

Fundamentally, the light intensity is modulated by a transducer device, guided to a detector and subsequently processed into electronic signals; to keep this type of sensor calibrated, it is necessary to have a reference mechanism that avoids errors due to optical power fluctuations in the system due to the source, couplers, connectors or any optical component that may introduce significant relative errors and it is also important to consider that they suffer from an unstable measurement caused by the uncertain curvature of the fiber (Di *et al.,* 2018).

Interferometry-based sensors: This type of optical sensor better known as Fabry-Pérot interferometer, consists of a basic structure of two flat and parallel surfaces with partial reflectivity that create interference patterns as exposed by García *et al.* (2010). In the first type, partial mirror surfaces must be created inside the fiber by chemical or fusion processes; on the other hand, in the extrinsic version of the interferometer, the optical cavity is external to the fiber and is kept aligned by means of an attached capillary tube (García *et al.*, 2010). Although well-structured arrays can be built using this type of sensors and present characteristics such as high coupling efficiency, stability, ease of alignment, good resolution, accuracy and become considered the most popular technique for vibration detection in the area of fiber optics, it suffers from a limitation of bandwidth and a complicated measurement system at a high price (T. Li, Guo, *et al.*, 2020).

Wavelength-based sensors: Fiber optic Bragg grating sensors have been used since 1988 to measure deformations and temperatures, from the multiple advantages they present such as those mentioned above, which have led to a significant increase in the amount of developed works where FBGs are implemented to measure vibrations (Garcia *et al.*, 2010).

Vibrations induce high-speed dynamic deformation variations and monitoring the position of the FBG resonance wavelength allows measuring those vibrations, despite the fact that to detect high-frequency vibrations, high-speed interrogation techniques are needed. These fiber optic sensors offer accurate, durable and inexpensive configurations for measuring vibrations, which expands the range of applications, opens new fields of research and makes them excellent candidates for measuring vibrations; therefore they are the type of sensor to be employed in the development of this study and further study of these is discussed below (T. Li, Pan, *et al.*, 2020).

## Approach to vibration studies using FBG

Within the multiplicity of applications of FBG sensors, through the study of previous research for the development of this research, it was possible to identify two approaches directly related to the branch of mechanics and civil infrastructure.

The first one deals with the development of optical sensors of the accelerometer type using FBG and the second one about experimental arrays built for the monitoring of engineering systems.

The first of these approaches, is related according to the vibration-strain coupling difference of FBG, these vibration sensors can be classified into three categories, which are mentioned by Li, Guo *et al.* (2020) and described as follows.

1) Vibration sensors based on bonded FBG: These sensors are responsible for converting the vibration signal into the surface tension of the elastomer (usually a beam in cantilever configuration) detected by the bonded FBG as shown in Figure 3, this configuration is the most widely used due to its simple principle and structure (T. Li, Guo, *et al.*, 2020).

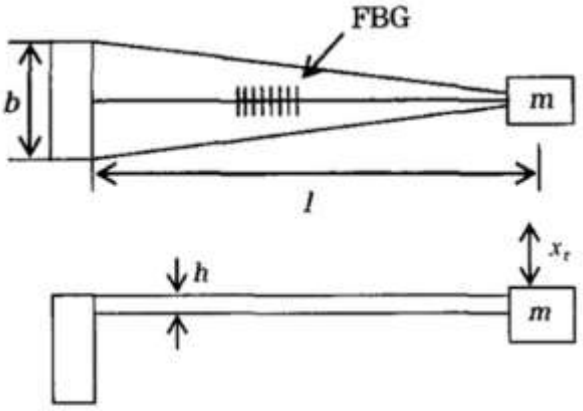

**Figure 3** Sensors based on glued FBG
*T. Li, Guo, et al., 2020*

2) FBG axial property based vibration sensors: The axial property of the FBG based vibration sensor is adjusted by suspending the FBG in the sensor configuration instead of a bonded FBG as shown in Figure 4 (Basumallick *et al.*, 2020). Going into detail, these configurations are more complex since a mass is incorporated in the center of such a fiber with both ends attached to the base of the sensor and elastomer, respectively; where vibration along the length of the fiber must be converted into compression or tension of the FBG (T. Li *et al.*, 2017).

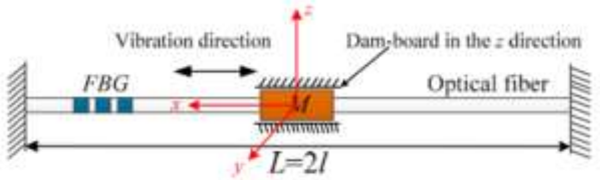

**Figure 4** Sensors based on the axial property
*T. Li, Guo, et al., 2020*

3) Vibration sensors based on the transverse property of FBG: Similarly, both ends of a FBG are fixed to design the transverse property of vibration sensors as presented in Figure 5; despite this, the inertial force of the vibrating mass is exerted in the transverse direction instead of the direction along the fiber length (K. Li *et al*., 2014). These configurations can amplify the compression or tension of the FBG, leading to higher sensitivity for a transverse force compared to the axial force along the fiber (K. Li *et al*., 2014; T. Li, Guo, *et al*., 2020).

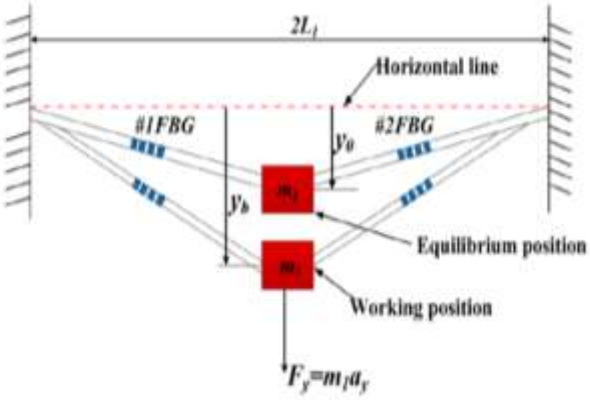

**Figure 5** Sensors based on the transverse property
*T. Li, Guo, et al., 2020*

Until these days, a considerable number of optical accelerometer designs employing FBG have been developed, which aims to achieve a high frequency measurement response range and the development of techniques to considerably increase the sensitivity, which make this approach as a potential option for monitoring the vibrational responses of the experimental platform.

The second approach to the construction of experimental arrays for the monitoring of vibrating systems, basically consists of placing an FBG sensor on the structure to be analyzed; this is because any change in deformation, temperature and vibration is transmitted directly on the grid in terms of wavelength shift, as argued by Goossens *et al*. (2021). The way of placing the FBGs can be in the form of minimal intrusion in the case of insertion or mounted on the surface to be analyzed. Davis *et al*. (1996) state that it is important to be aware that one of the challenges is the location of the sensors throughout the structure, and one must be meticulous with the method of attachment or insertion of the sensors as it may present problems in the long term due to the effects present in the material.

From the above, there are details regarding how fibers are inserted into the material, while benefiting from intrinsic protection from the host material conditions, not all manufacturing methods in the case of composite materials allow for fiber insertion, in addition; it can be challenging to ensure the optical connection reliability of the sensor and in case of failure it is difficult to repair the fibers; these limitations can restrict the implementation of fibers in many composite applications (Goossens *et al*., 2021).

The amount of research related to this type of approach is very reduced; this is a consequence of the need for interrogation systems with peculiar characteristics, which will be discussed below. In this sense, some of the works of relevance are that of Rajan and Karekal (2017), which deals with a study of rock cracking events for mining applications adjunctly employing an FBG sensor for acoustic emission monitoring, using a high frequency FBG interrogation system with sampling capacity of 1.16 MHz.

Another work is presented by Kim *et al*. (2022), which deals with an experimental study in which several FBG networks are used to detect vibro-acoustic signals from leaking water pipes using an interrogation system with 3 kHz sampling capability. Similarly, Tozzetti *et al*. (2021), showed an experimental study about dynamic deformation measurements in gasoline direct injectors where FBGs were placed on the surface of a valve body along the axial direction, this employing an interrogation system with measurement capability up to 240 MHz.

And finally Jang and Kim (2017), developed a study of low-velocity impact-induced delamination in carbon fiber reinforced polymer laminates where several FBGs were bonded to the laminate surface and implementing a high-speed interrogation system with a relatively low sampling frequency of 100 kHz.

Given the simple and multitasking characteristics of the implementation of this type of approach, despite the limitations described above, it is undoubtedly a good option for monitoring the vibrational analysis of the experimental platform.

## Monitoring systems using fiber optics with Bragg gratings

Going deeper into the two previous approaches described above, the use of two types of instruments for the optical monitoring system was identified, the first one through the use of modulators and the second one using interrogators. Since part of the objective of the study is conditioned to the use of the si425 optical interrogator, the review of these monitoring systems was limited to this type of optical instruments.

In most of the researches, sophisticated vibration detection systems are developed for vibration monitoring in a high frequency measurement range, allowing the use of a wide range of electro-optical components adjusting to the required needs and available economic resources, such as the monitoring systems developed and described below.

One of the most outstanding developments is that of Kim *et al*. (2022), where they conceived a spectrometer-type interrogation system where the reflected wavelengths feed a photodiode array module through a fiber optic circulator to demodulate the Bragg wavelength. Buck *et al*. (2012), on the other hand, designed a highly integrated interrogator based on an ordered waveguide grating, specially constructed for the acquisition of dynamic structural loads. Xiong *et al*. (2021), generated an eight-channel FBG wavelength interrogator to achieve real-time wavelength recording outputs under the spectroscope-type operating principle with an acquisition frequency of 10 Hz.

On the other hand; Yamaguchi and Shinoda (2015), established a fast wavelength-scanning laser interrogator capable of measuring vibrations with sampling frequency of 20 MHz. And by Isago and Nakamura (2009), they contributed a FBG sensor array system employing a high-speed 172 kHz high-speed scanning light source.

However, there are also works where commercial interrogators are used such is the case of Fan *et al*. (2011), where they performed surface testing and identification of vibration parameters using a Micron Optics si425 interrogator, which works as a scanning laser system, capable of an acquisition frequency of 250 Hz. One of the widely used interrogators is the SM130 from Micron Optics which operates as a scanning laser system and is used by Basumallick *et al*. (2020) and Xu *et al*. (2020), respectively; for recording the response of FBG accelerometers with a scan rate of 2 kHz and in acceleration tests from 1 to 100 Hz. Another type of commercial interrogators with outstanding characteristics are those employed in research such as Zhang *et al*. (2007), where they used a high-speed CGT (Circulating Grating Transform) interrogator developed by ITF Labs which reaches a sampling rate of up to 5 kHz and the Thor-LABS alternative interrogation system with 1 kHz interrogation capability operating under the spectroscopy operating principle employed by Macedo *et al*. (2023).

## Proposed vibrational monitoring system

To determine the best solution to our identified problem, it is known that; the experimental platform reaches an angular velocity of 3600 RPM, equivalent to a frequency of 60 Hz, from this, it is proposed that the experimental instrumental system to be developed for the dynamic monitoring of the experimental platform, using an optical detection interrogator model si425 of the manufacturer Micron Optics; is the construction of the experimental arrangement using FBG sensors which are attached to the surface of the platform, as shown in Figure 6, so that any change in terms of vibration is transmitted directly on the grid as a function of the wavelength shift.

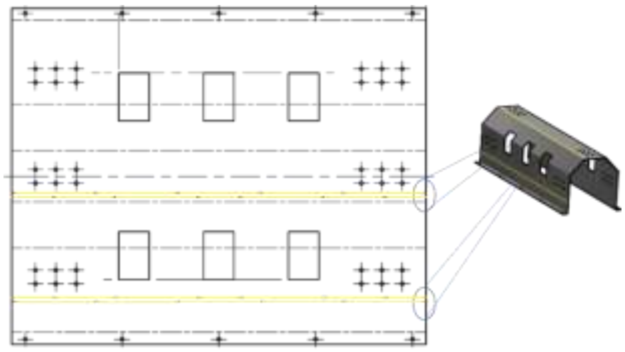

**Figure 6** Experimental setup using FBG adhered to the platform surface
*Author's development*

## Results

It was decided to choose to develop an experimental system where FBG sensors are attached to the platform because in this way through the multiplexing properties of the FBG more points can be obtained to analyze on the platform, in addition; although the development of optical accelerometers using FBG sensors presents a potential growth from the high sampling rates that can reach in the measurement range of up to MHz, for this application these high levels of vibrational analysis are not required; Therefore, the detection capabilities provided by these accelerometers would not be taken advantage of, added to this, the design of a FBG accelerometer requires great investment in economic terms, time and effort, which would delay the start of the experimental tests.

On the other hand, although to measure vibrations using FBG sensors, an interrogation system with a sufficiently high bandwidth is needed as described by García *et al*. (2010); in accordance with what is stated by Preizler *et al*. (2017), where they mention that the Nyquist theorem requires the sampling rate to be at least twice the bandwidth, assuming that the actual sampling takes an infinitely short time; in this sense by presenting the experimental platform with a sampling frequency 60 Hz, a bandwidth of 120 Hz is required in order to be able to perform the vibration measurement acquisition effectively, therefore; Although the si425 interrogator has a bandwidth of 250 Hz, which compared to the interrogation systems built in the research reviewed is very low, it has the capacity to be used in this experimental arrangement.

## Conclusions

In this study, the review of two of the main approaches in the experimental dynamic analysis of engineering systems using fiber optic sensors of the Bragg grating type was carried out, with the objective of identifying the best solution for the vibrational analysis of the experimental platform presented and the use of the si425 optical interrogator, the proposal of an experimental arrangement was selected, which fits perfectly to the characteristics of the vibrational analysis to be carried out in the future, which can contribute in an extrapolated way to more detailed dynamic studies such as modal analysis and the estimation of aircraft propulsion systems balancing, which would benefit the maintenance procedures in the industry in such a way that the structural health of the aircraft and the physical and mental integrity of the passengers are taken care of. In addition to this, the presented review can contribute to the decision making process of other studies where the selection of an instrumental proposal for vibrational analysis is required.

## Acknowledgments

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