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Design and Development of an Optical Vibration Sensor Based on Fiber Bragg Grating (FBG) Technology for Aerospace Applications / Bertone, M., Aimasso, A., Amoretti, F., Maggiore, P., Dalla Vedova, M.D.L.. - In: JOURNAL OF PHYSICS. CONFERENCE SERIES. - ISSN 1742-6588. - 3179:(2026). (16th International Conference on Vibration Measurements by Laser and Noncontact Techniques, AIVELA 2025 Ancona (ITA) 24/06/2025 - 26/06/2025) [10.1088/1742-6596/3179/1/012003].

Availability:
This version is available at: 11583/3016826 since: 2026-10-20T10:05:14Z

Publisher:
Institute of Physics

Published
DOI:10.1088/1742-6596/3179/1/012003

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19 November 2026

Journal of Physics:
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To cite this article: Matteo Bertone *et al* 2026 *J. Phys.: Conf. Ser.* **3179** 012003

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Design and Development of an Optical Vibration Sensor Based on Fiber Bragg Grating (FBG) Technology for Aerospace Applications

Matteo Bertone [1], Alessandro Aimasso [1], Fabio Amoretti[1], Paolo Maggiore [1] and Matteo Davide Lorenzo Dalla Vedova [1]

[1]Dept. of Mechanical and Aerospace Engr., Politecnico di Torino, Turin, Italy

E-mail: matteo.dallavedova@polito.it

Abstract. Vibration analysis involves studying mechanical oscillations in systems caused by factors such as imbalances, misalignments, external forces, or internal dynamics. These oscillations may be periodic, random, or transient, and understanding their frequency and amplitude is essential for diagnosing mechanical issues, ensuring system stability, and optimizing performance. A key tool in vibration analysis is Fourier analysis, which enables the decomposition of complex vibration signals into their constituent frequency components. By transforming time-domain data into the frequency domain using the Fourier Transform, dominant frequencies, harmonics, and resonances can be more clearly identified. This method is particularly useful for detecting periodic disturbances or resonances within a system and is critical for applications such as condition monitoring, predictive maintenance, and system design optimization, where understanding vibration frequency content is vital for performance and reliability assessments. Leveraging the versatility of Fiber Bragg Grating (FBG) sensors, a carefully designed "comb structure" comprising teeth of varying lengths, each embedding an FBG sensor - can be constructed to mechanically approximate the frequency decomposition achieved through Fourier analysis. This structure functions similarly to a comb, with each blade tuned to a distinct resonant frequency, thereby isolating different frequency components based on the vibration response of each blade. Since achieving different resonant frequencies can be accomplished by simply scaling the geometry of a well-designed blade, this paper will focus on analyzing the design and results of the blade with the lowest resonant frequency.

1 Introduction

The study and monitoring of vibrations in rotating machinery is of considerable interest for assessing the operational condition of components[1][2]. In particular, the evaluation of the vibratory environment of electrical machines, which are finding widespread application in the

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aerospace sector, is extremely important. In such machines, vibration sources are numerous as they are not limited solely to the more intuitive mechanical nature, but also include electrical[3] and thermal origins.

The foundation of this research lies in Fiber Bragg Gratings (FBGs), which are optical structures fabricated within the core of optical fibers by inducing periodic variations in the refractive index. These variations, typically characterized by periods on the order of hundreds of nanometers, form a diffraction grating that functions as a wavelength-selective reflector. FBGs are sensitive to both mechanical[4] and thermal[5] perturbations, which manifest as shifts in the reflected wavelength, thereby enabling accurate measurement of various physical parameters.

In the context of aerospace electric machinery, the use FBG sensors allows for the mitigation of limitations associated with traditional sensors[6]. Indeed, this technology, being based on light radiation, exhibits natural immunity to electromagnetic interference, enabling more flexible sensor placement. Furthermore, since the waveguide is composed of silica, it is both resistant to high temperatures and electrically insulating, allowing it to withstand the temperatures[7] that can be generated during operation while simultaneously not constituting a source of short circuits.

Given the capability of utilizing FBGs operating at different wavelengths, this technology is well-suited for the development of complex and modular sensor networks[8]. Leveraging this versatility, a carefully designed comb structure comprising teeth of varying lengths can be constructed to mechanically approximate the frequency decomposition achieved through Fourier analysis. This approach reduces the need for extensive data processing. Furthermore, it enables the selection of frequencies most appropriate for monitoring the desired phenomena.

2 Design description

Given the extreme fragility of optical fiber, a fundamental aspect that was taken into account during the sensor design was the necessity to guarantee an adequate level of protection along the entire section affected by the sensor. In particular, given the characteristic of FBG sensors to respond with wavelength variations to mechanical deformations, it was decided to adopt an oscillating blade as a pick-up element, following the approach proposed by Basumallick et al. [9]. This geometry allows for the limitation of oscillations in undesired directions, presenting a notable similarity in response to that of a cantilever beam. Using this approximation, it was therefore possible to employ analytical formulas for the preliminary estimation of the geometry. Specifically, the resonance frequency of a cantilever beam is related to the structural properties by the following relationship:

$$f_n = \frac{K_n}{2\pi L^2}\sqrt{\frac{EI}{m}} \tag{1}$$

where:

- f_n = resonant frequency.
- K_n = coefficient dependent on the mode ($k_1 = 3.52$).
- L = beam length.
- E = Young's modulus.
- I = moment of inertia.
- m = mass per unit length.

This analytical approach, although computationally efficient when all parameters are known, was restricted to the preliminary design phase due to the numerous geometric modifications implemented at each design iteration, which would have required repeated re-estimation of all necessary parameters. The design process involved iterative refinement aimed at reducing the

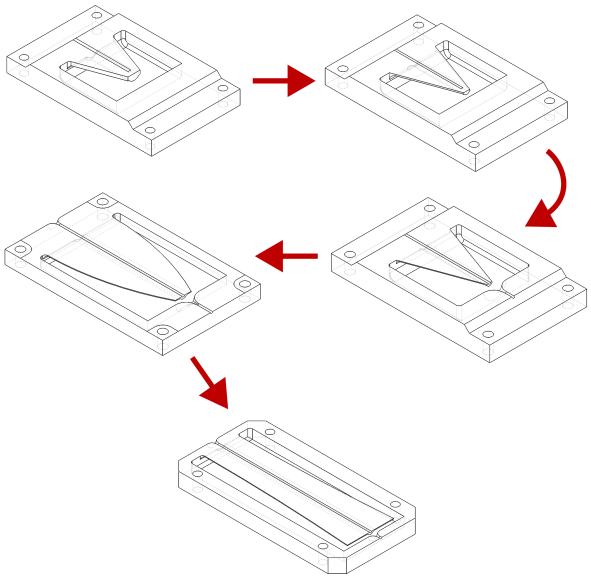


Figure 1: Evolution of the internal cross-section of the sensing element.

overall dimensions while simultaneously attaining the minimum achievable resonant frequency. This optimization presented inherent design trade-offs, since the resonant frequency of slender cantilever structures exhibits an inverse relationship with length. Through FEM analysis of the first resonant frequency, multiple design configurations were evaluated and rejected as inadequate. The optimized final design comprises a 65 mm blade with a first resonant frequency of 57.12 Hz, as determined by FEM simulation. The numerical analysis modeled the blade as a cantilever structure with fixed boundary conditions at the mounting interface with the protective case.

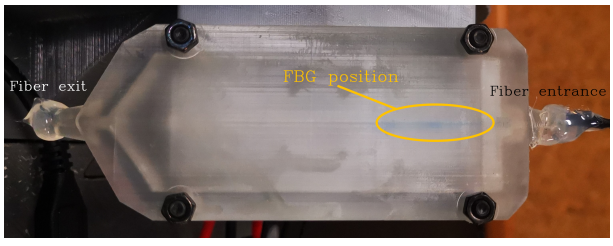


Figure 2: Final prototype

The final design of the sensing element and its protective casing resulted in a structure consisting of a blade reinforced by a central element that serves to guide and protect the optical fiber, enclosed in a housing terminating with a V-shaped configuration at the free end of the blade, as depicted in Fig. 2. This geometric feature is extremely important for both the manufacturing phase and the actual assembly process. The shape enables the component to

be produced as a single piece, thereby limiting structural discontinuities and the possibility of external elements contaminating the chamber containing the sensing element. Furthermore, the conical shape naturally facilitates the alignment of the fiber with the exit channel during assembly, reducing the risk of jamming and eliminating sharp corners that could potentially damage the fiber.

The assembly phase involved threading the fiber through the guide to position the FBG at the root of the blade. This location experiences the highest stress concentration and consequently represents the optimal position to minimize noise effects on the measurements. Final fixation was achieved by gluing the fiber at the exit point of the casing.

3 Experimental validation

In order to verify the proper functioning of the final design, tests were conducted on the prototype. The principle underlying the adopted experimental setup was to excite the blade with an impulse, since a perfect theoretical impulse has a constant Fourier transform, implying a uniform magnitude spectrum over the entire frequency range. This means that an impulse excites all frequencies equally, and is therefore the most suitable input for the test. To produce the impulse, the blade was positioned at the center of a steel plate whose four corners were simply supported on metallic stands as shown in Fig. 3. This setup was then placed on a rubber-coated table in order to isolate it as much as possible from external vibrations. To generate the impulses, metallic weights were dropped onto the corners one at a time. Lastly, the FBG interrogator

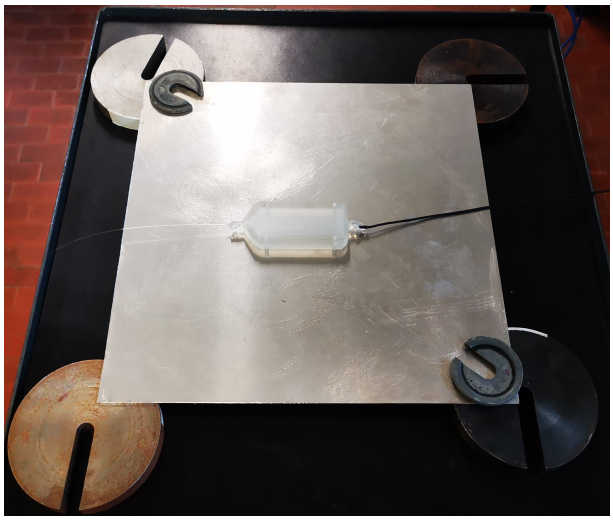


Figure 3: Experimental setup for impulse-based testing of the blade

acquisition frequency was set to 2.5 kHz to enable analysis of a wider frequency range.

The power spectrum derived from the measurement is shown in Fig. 4. As can be observed, the two highest peaks occur at 47.45 Hz and 57.44 Hz, while a pronounced dip appears between them at 52.45 Hz. Recalling that the FEM analysis predicted a resonant frequency of 57 Hz, it can be noted that the predicted frequency is close to the second highest peak. The most reasonable explanation for the overall shape of this portion of the spectrum is that the actual resonant frequency corresponds to the dip at 52.45 Hz. This behavior can be explained by the sensor losing contact with the blade when resonance occurs. This phenomenon is further supported by the limited bonding surface area available in the prototype.

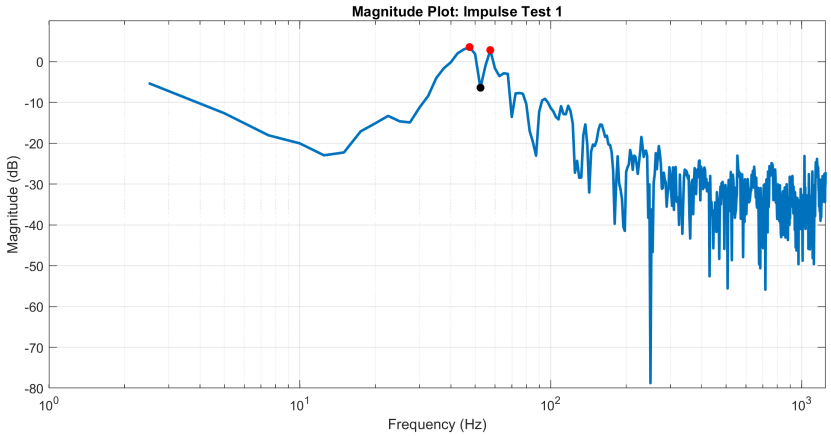


Figure 4: Power spectrum for the impulse test response

Attributing the dip to tribological effects, the discrepancy between the experimental and simulated resonant frequencies is less than 10%, with higher frequencies being successfully attenuated, which demonstrates promising results.

4 Conclusions

In conclusion, the prototype was installed on a test bench for electric motors, allowing for the evaluation of its response under more representative conditions. In this scenario, the amplitude of oscillations was measured as a function of the rotational speed of the motor under test. Despite the low power levels involved (below 24 W), the sensor was able to clearly detect the vibration frequencies of the system. This test, as shown in Fig. 5, easily demonstrated that all resonance peaks shift to higher frequencies as throttle increases, with higher-frequency peaks exhibiting a more rapid shift than those initially appearing at lower frequencies.

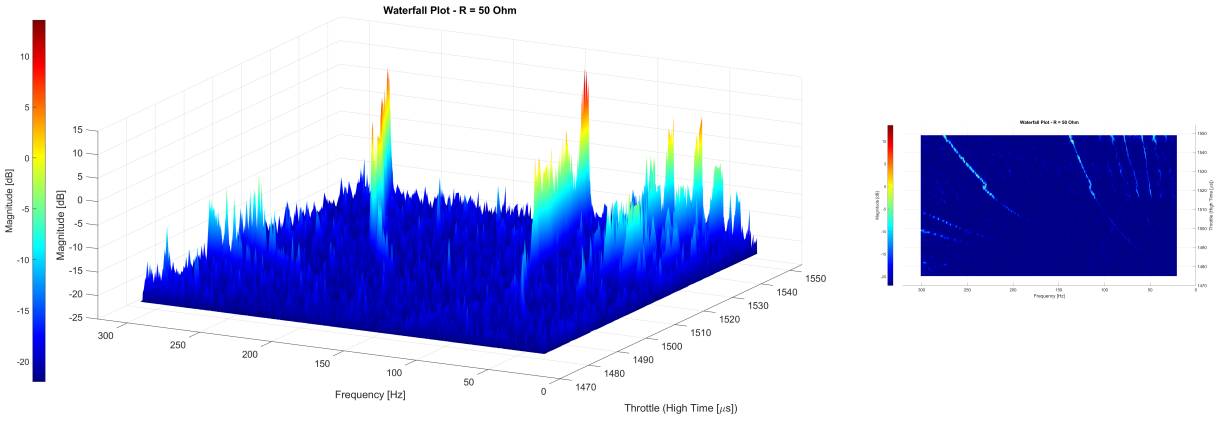


Figure 5: Power spectra for different throttle settings shown in 3D on the left and in 2D on the right

The prototype has therefore demonstrated good agreement with design expectations, representing a customizable element for specific frequencies. Furthermore, given the compact dimensions of the FBGs, it can be easily integrated into more complex comb-like structures in which individual blades are tuned to specific frequencies of interest.

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