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Enhancing Industrial Operations through Integrated FBG Vibration Sensors in Predictive Maintenance Decision Support Systems

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Abstract: In the industrial environment of today, maximizing operations and reducing downtime are essential objectives. By enabling proactive equipment servicing based on real-time data insights, the advent of Predictive Maintenance (PM) has completely transformed asset management. This study aims to determine whether Fiber Bragg Grating (FBG) vibration sensors can be integrated into a Decision Support System (DSS) to improve PM in industrial operations.
Method: The methods used in this study include a thorough analysis of the vibration of a rotating machine by acquiring real-time vibration signals from the FBG sensor and integrating a DSS scheme for predictive decisions. An experimental case study is also portrayed to showcase the practical approach.
Findings: A rotating machine is used to measure vibration using a conventional piezoelectric sensor. Simultaneously, an FBG sensor is also installed to perform similar vibration measurement activity, and the real-time signal from the FBG sensing setup is acquired to highlight the experimental use case. It is found that the FBG sensor performs high precision sensing with a wide span of frequency spectrum.
Novelty: The FBG sensor signal is largely influenced by noisy components and the effect of the noisy signature needs to be nullified before analyzing the spectrums. A pre-processing scheme is implemented to nullify the effect of noisy signatures present in the raw signal. A decision support system receives the sensor data and uses machine learning algorithms to analyze and interpret it. Machine faults can be identified from the vibration signatures of the FBG sensors. The results of this study demonstrate the significant advantages of FBG vibration sensors in preventive maintenance and DSS. As a result, maintenance tasks can be scheduled throughout pre-arranged downtimes, minimizing operational disruptions and related expenses. This strategy is novel because it combines cutting-edge FBG sensor technology with a decision support system to provide a complete answer for improving industrial operations through preventive maintenance.

Keywords: *Predictive Maintenance, Fiber Bragg Grating, Vibration Sensors, Decision Support System, Vibration Measurement.*

1. Introduction:

The pursuit of operational excellence and cost-effectiveness has changed maintenance strategies in the dynamic environment of contemporary industries [1]. Predictive maintenance, which uses real-time data and cutting-edge analytics to predict equipment failures and optimize maintenance schedules, is replacing traditional reactive and PM approaches [2, 3]. In this context, FBG vibration sensors have become a cutting-edge technology for precise data collection. An in-depth discussion of the integration of FBG vibration sensors into a DSS is highlighted in this article; outlining a cutting-edge strategy for redefining PM. Predictive maintenance increases the lifespan of industrial assets while minimizing unscheduled downtime. A novel approach for monitoring equipment conditions is provided by FBG sensors, which are renowned for their high precision and resistance to environmental influences [4, 6]. To forecast anomalies and trends, industries can take advantage of advanced analytics by incorporating FBG sensor data into a DSS. As a result, a thorough maintenance strategy is produced that not only anticipates failures but also optimizes resource usage. To improve PM and ultimately create more effective and proactive industrial operations, this paper examines the goals, processes, results, and novelty of incorporating FBG vibration sensors into a DSS. Based on the above discussions, the research gaps and areas for further investigation can be identified as follows:

a) **Optimization of Noisy Signal Handling:** The study highlights the influence of noisy components on FBG sensor signals and the implementation of a pre-processing scheme to mitigate this effect. However, there is a research gap in further optimizing and enhancing this pre-processing scheme to effectively handle a wider range of noisy signatures, ensuring higher accuracy in fault detection and maintenance decision-making.
b) **Study and analysis of sensor data:** The study incorporates algorithms for the analysis and interpretation of sensor data. A research gap lies in exploring algorithms to identify the most effective and efficient ones for fault detection and prediction based on FBG sensor data.
c) **Integration of FBG Sensors in Diverse Industrial Machinery:** The experimental case study focuses on a rotating machine, providing valuable insights into FBG sensor performance. However, there is a need for further research encompassing a broader spectrum of industrial machinery and equipment. Investigating the adaptability and efficacy of FBG sensors in various types of machinery will enhance the applicability and generalizability of the proposed approach.
d) **Real-World Implementation and Scalability:** The study presents a practical approach through an experimental case study; however, a research gap exists in evaluating the scalability and real-world implementation of the proposed integrated FBG sensor-DSS system across a range of industrial setups. Assessing the system's performance in diverse operational conditions and different industry sectors will validate its effectiveness and practicality on a larger scale.

This article presents a methodology to implement an integrated IoT-enabled vibration monitoring system using FBG sensors. To underscore the relevance of such systems in vibration monitoring applications, the article is structured into eleven sections. The second section discusses the scope of the work followed by a thorough literature review section. The fourth section covers the methodology followed by the limitations of the proposed methodology. The sixth section highlights the proposed objectives and the principle of FBG sensor is discussed in the seventh section of the article. The eighth section portrays the details of the experimental setup followed by DSS. Finally, the last section highlights the conclusion of the proposed work followed by the future scope and reference section.

2. Scope of the Work

The research aims to revolutionize predictive maintenance within industrial operations by harnessing the capabilities of FBG vibration sensors. By integrating these sensors into a sophisticated decision support system, the study intends to foresee potential equipment failures through real-time data insights. This proactive approach enables the formulation of optimized maintenance strategies, minimizing downtime and enhancing resource allocation. Employing FBG vibration sensors and advanced machine learning algorithms holds the promise of vastly improving the precision and efficacy of preventive maintenance, ultimately reducing operational costs associated with traditional maintenance methods. The proposed research work presents two broad scopes:

- **Enhancing Predictive Maintenance in Industrial Operations:** The research aims to leverage FBG vibration sensors in a decision support system to enhance predictive maintenance in industrial settings. This approach is designed to anticipate equipment failures based on real-time data insights, leading to proactive maintenance strategies that minimize downtime and optimize resource allocation. By incorporating FBG vibration sensors and machine learning algorithms into the decision support system, the study seeks to improve the precision and efficacy of preventive maintenance, ultimately reducing operational costs associated with traditional maintenance strategies.

- **Integrating FBG Vibration Sensors for Early Anomaly Detection:** The research delves into integrating FBG vibration sensors into a decision support system to facilitate early anomaly detection in industrial equipment. The focus is on utilizing advanced analytics and machine learning to analyze sensor data, enabling accurate predictions of equipment failures. The integration of FBG sensors allows for the timely identification of anomalies, empowering maintenance teams to schedule proactive maintenance tasks during planned downtimes. This integration strategy minimizes operational disruptions, demonstrating the potential for a comprehensive solution that optimizes industrial operations through proactive maintenance.

3. Literature Review

The review of the literature reveals a variety of studies covering various facets of sensor, IoT, AI, and predictive maintenance technologies. Predictive maintenance is stressed within the context of Industry 4.0 [1]. The machine learning approach in smart manufacturing based on predictive maintenance in Industry 4.0 is briefly explained [2]. It focuses on using machine learning techniques and real-time IoT data to improve maintenance procedures in manufacturing. The use of smart manufacturing in rolling processes is examined [3], with a focus on thermal safety monitoring. It talks about how fiber optic sensors can be installed in mill bearings to increase their efficiency and safety. Modern reviews of intelligent condition monitoring in wind power systems are the major focus points [4]. It covers a range of methods and tools for keeping track of and maintaining wind turbines. A fiber Bragg grating-based torsional vibration sensor for monitoring rotating machinery is presented [5]. The use of this sensor technology in industrial settings is covered. The integration of optical fibers and nanomaterials for multifunctional applications in aircraft systems is described [6]. It talks about potential innovations and upgrades to aviation technology. It talks about using fiber optic sensors to outfit mill bearings with improved safety features. A fiber Bragg grating-based accelerometer is proposed in a preliminary study for the purpose of observing the vibration of a prototype industrial engine [7]. In the context of Industry 4.0, the performance analysis of chirped fiber Bragg grating-based abrasion sensors for maintenance applications is portrayed [8]. The integration of artificial intelligence and predictive maintenance in electric vehicle components, with an emphasis on optical and quantum enhancements, is offered [9]. These studies show the need for more in-depth studies on the integration of FBG sensors into decision support systems for improved predictive maintenance in industrial operations. Collectively, these studies offer valuable insights into the broader landscape of predictive maintenance and sensor technologies.

Table 1: Relevant literature and limitations of the proposed techniques

Study	Key Findings	Limitations
[1] T. Zonta et al. (2020)	Focuses on predictive maintenance in Industry 4.0.	Limited focus on practical implementation and real-world case studies.
[2] A. Serkan, A. Koray (2021)	Utilizes machine learning and IoT data for predictive maintenance in manufacturing.	Limited discussion on the scalability and adaptability of the system. Lack of comparison with existing predictive maintenance solutions.
[3] E. Brusa et al. (2022)	Focuses on smart manufacturing with thermal safety monitoring using fiber optic sensors.	Limited information on cost-effectiveness.
[4] M. Benbouzid et al. (2021)	Offers a state-of-the-art review of intelligent condition monitoring in wind power systems.	Scalability and long-term performance not discussed
[5] C. Marques, A. Leal-Júnior, S. Kumar (2023)	Explores multifunctional integration of optical fibers and nanomaterials for aircraft systems.	No real-world implementation
[6] S. Mariana et al. (2022)	Presents a preliminary study on Fiber Bragg Grating-based accelerometers for monitoring industrial engine prototype vibrations.	Scalability and long-term performance not discussed
[7] M. Konrad et al. (2020)	Analyzes the performance of Chirped Fiber Bragg Grating-based abrasion sensors for Industry 4.0 maintenance applications.	The study may not provide insights into the long-term durability and reliability of the sensors.
[8] P.S. Rao et al. (2023)	Likely discusses the integration of AI and optical/quantum enhancements in predictive maintenance.	The study does not compare the integrated AI, optical, and quantum enhancements with alternative

		predictive maintenance approaches
[9] Ho, HW. et al. (2022)	Likely discusses the application of Fiber Bragg Grating sensors in structural health monitoring.	Limited discussion on the scalability of the approach to larger robotic systems.

In summary, the literature review provides an extensive overview of studies encompassing sensor technologies, the Internet of Things (IoT), Artificial Intelligence (AI), and Predictive Maintenance (PM). The focal point is predictive maintenance in the context of Industry 4.0, exploring recent advancements and their integration with Industry 4.0 technologies [10]. Several studies emphasize predictive maintenance systems using machine learning and real-time IoT data for enhancing manufacturing maintenance procedures [11, 12]. Fiber optic sensors, particularly Fiber Bragg Grating (FBG) sensors, play a vital role in these studies, demonstrating their potential in monitoring machinery, improving safety, and enabling condition monitoring [13, 14, 15]. The integration of optical fibers, nanomaterials, and advanced sensor technologies into various industrial applications, including wind power systems and aviation technology, is also explored [16, 17, 18]. While the literature review provides a comprehensive understanding of the landscape of predictive maintenance and sensor technologies, a notable research gap lies in the need for deeper investigations regarding the integration of FBG sensors into decision support systems for significantly improving predictive maintenance in industrial operations [19, 20]. The studies reviewed offer valuable insights but highlight the necessity for further research that delves into the practical implementation and optimization of FBG sensors within decision-support frameworks. Additionally, more studies are needed to explore novel applications and advancements in integrating artificial intelligence and quantum enhancements into FBG sensors for predictive maintenance in various domains, with a focus on scalability, accuracy, and real-world deployment. Closing these gaps will advance the field by contributing practical solutions to enhance predictive maintenance strategies in Industry 4.0.

4. Methodology

The methodology involves a systematic approach that covers sensor deployment, data acquisition, processing, analytics, and decision-making which are represented in Figure 1. FBG vibration sensors are used to monitor vibration in a decision support system for enhanced predictive maintenance.

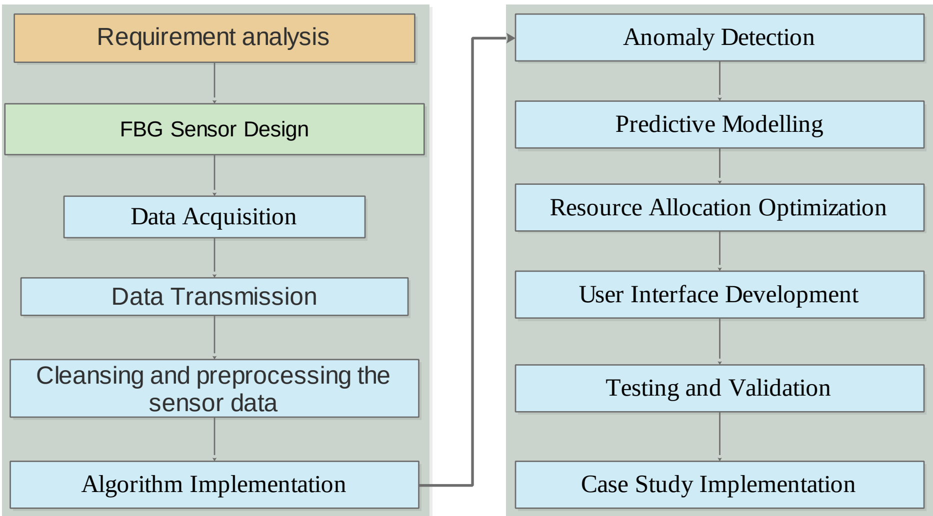

Figure 1: The systematic approach of the Methodology

The methodology is outlined in the following steps:

a) **Requirement analysis:** List the precise industrial assets and machinery that FBG sensors will be used to monitor. Establish the frequency of data collection and the essential measurements (such as vibration frequency and amplitude).
b) **FBG Sensor Deployment:** Position FBG vibration sensors on the equipment of choice. For accurate data collection, place the sensors in the proper locations. Think about things like sensor orientation and attachment techniques.

c) **Data Acquisition:** Set up a system for gathering data in real-time from the deployed FBG sensors. Use optical interrogators to record the wavelength changes in the reflected light from the FBG sensors, which correspond to the vibrational characteristics of the apparatus.
d) **Data Transmission:** Set up a dependable network to send sensor data to a central database or cloud-based platform. Make sure that data is transmitted securely and with integrity.
e) **Cleansing and preprocessing the sensor data:** For accurate analysis, normalize the data and align it to a constant time scale.
f) **Development of a Decision Support System:** Create a decision support system that incorporates the gathered FBG sensor data. Algorithms for data analysis, anomaly detection, and predictive modeling should be included in this system.
g) **Algorithm Implementation:** Apply cutting-edge analytics algorithms to examine the information from the FBG sensor. To find patterns and anomalies in the vibration data, use machine learning techniques like clustering, regression, and classification.
h) **Anomaly Detection:** Create algorithms that can identify changes in an item's typical behavior. Set acceptable vibration thresholds and configure the system to send alerts when anomalies are found.
i) **Predictive Modelling:** To create predictive models, combine historical data with the most recent sensor readings. These models ought to forecast the likelihood of upcoming failures and estimate the remaining useful life of equipment components.
j) **Resource Allocation Optimization:** Include decision-making algorithms that rank maintenance tasks according to the seriousness of anomalies that have been found and the likelihood that they will fail in the future. Allocating resources for maintenance tasks should be optimized.
k) **User Interface Development:** Real-time visualizations of sensor data, anomaly alerts, and predictive knowledge should all be available through this interface.
l) **Testing and Validation:** Test the integrated system using simulated data in a controlled environment or, on a smaller scale, in a real industrial environment. Verify the precision of the capabilities for anomaly detection and prediction.
m) **Case Study Implementation:** Set up an industrial environment with an integrated FBG sensor and decision support system. Check the equipment over a predetermined time period to confirm the system's ability to spot anomalies and foretell failures.

5. Limitation of Methodology

The methodology outlined, while providing a structured approach to integrate FBG vibration sensors into a decision support system, does come with certain inherent limitations. First and foremost, ensuring accurate calibration of FBG sensors is vital for the methodology's success, but achieving precise calibration can be challenging due to factors like environmental conditions and sensor aging. Additionally, maintaining reliable and efficient data transmission from these sensors to the DSS proves to be a hurdle, particularly in settings with electromagnetic interference or signal loss. The computational complexity of advanced analytics and machine learning algorithms, integral to the methodology, poses a real-time management challenge, especially when dealing with many FBG sensors continuously generating data streams. Lastly, the effectiveness of the methodology relies heavily on the accessibility and quality of historical data for developing predictive models. However, historical data may not always be complete or accurate, which can significantly impact the reliability and accuracy of the predictive models generated. Acknowledging and addressing these limitations is crucial for refining the methodology and optimizing its performance in practical industrial applications.

6. Objective of Proposed Method

To improve predictive maintenance procedures in industrial operations, the goal of this study is to investigate the integration of FBG vibration sensors into a decision support system. The main goal is to create a framework for precise anomaly detection, predictive modeling, and real-time decision-making by utilizing the high-precision data gathered by FBG sensors. This research aims to optimize maintenance scheduling, decrease downtime, increase equipment lifespans, and ultimately enhance overall operational efficiency by combining advanced data analytics and the capabilities of FBG sensors. Through the incorporation of FBG vibration sensors into decision support systems, the proposed work seeks to advance predictive maintenance strategies by providing a more proactive approach to asset management in industries.

7. Working Principle of Fibre Brag Grating (FBG)

FBG technology is one of the most admired options for optical fiber sensors due to its simple manufacturing and reasonably powerful reflected signal. To generate FBGs, the longitudinal index of refraction of the fiber core is modulated regularly. They are systems that rely on the theory of diffraction gratings. The term "grating" is the periodic change of the refractive index of the core. When light passes over the grating surface some of the light is reflected and the rest of the light is received at the output of the fiber. The combination of all reflected light results in a single reflected beam of light and meets the Brag condition. The grating can reflect the light waves and act as a mirror or filter. When the FBG is subjected to external forces such as strain and temperature then its grating period and refractive index will be changed. The wavelength of light λ_B depends on the grating period Λ and effective index of refraction of the core N_{eff} which is explained in equation 1.

$$\lambda_B = 2\, N_{eff}\, \Lambda \qquad (1)$$

Where N_{eff} denotes the effective core refractive index, Λ is the grating period that determines the separation between two adjacent grating planes, and λ_B denotes the Bragg wavelength [15]. The principle of FBG is explained briefly and represented in Figure 2.

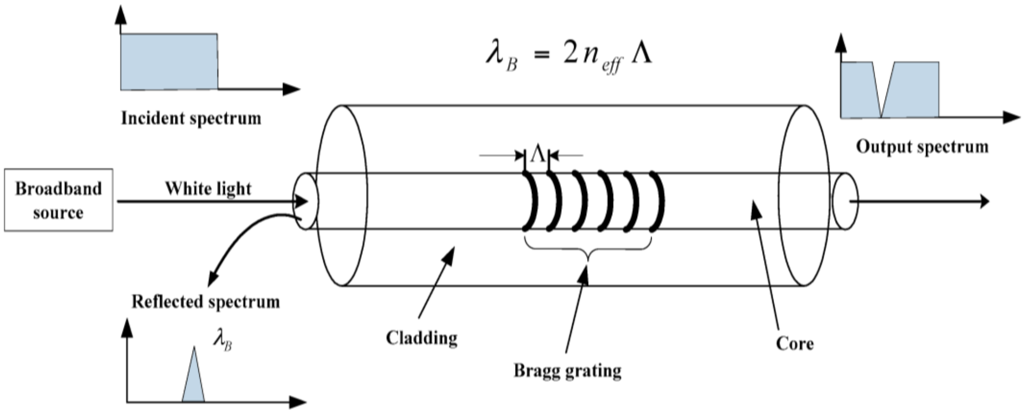

Figure 2: Basic working principle of FBG

When the Bragg condition is satisfied, the backward reflected peak, whose central wavelength is determined by λ_B, is formed. The Bragg wavelength shifts in an increase or decrease are closely related to the original wavelength. The shift in Bragg wavelength concerning the change in refractive index ($\Delta\eta_{eff}$) and change in grating period ($\Delta\Lambda$) is illustrated in equation 2.

$$\Delta\lambda_B = 2\, \Delta\eta_{eff}\, \Lambda + 2\, \eta_{eff}\, \Delta\Lambda \qquad (2)$$

Dividing equation (2) by equation (1)

$$\frac{\Delta\lambda B}{\lambda B} = \frac{2\,\Delta\,\eta eff\,\Lambda + 2\,\eta eff\,\Delta\Lambda}{2\,\eta eff\,\Lambda} \qquad (3)$$

$$\frac{\Delta\lambda B}{\lambda B} = \frac{\Delta\,\eta eff}{\eta eff} + \frac{\Delta\Lambda}{\Lambda} \qquad (4)$$

The shifting of Bragg wavelength ($\Delta\lambda_B$) depends on the temperature variation of the FBG, where $\frac{\Delta\Lambda}{\Lambda} \ll \frac{\Delta\,\eta eff}{\eta eff}$.

The Bragg period is considerably smaller as compared to the change in refractive index (ΔN_{eff}) with a temperature variation.

FBG sensor was designed by considering the above-mentioned reason and employing a slab-type structure to obtain larger fiber elongation. Thus, the sensitivity of the sensor resulted in a higher range. Equations 5 and 6 can be used to show how temperature affects the Bragg wavelength shift ($\Delta\lambda_B$).

$$\frac{\Delta\lambda B}{\lambda B} = (1 - Pe)\Delta\varepsilon + \left[\frac{1}{\Lambda}\frac{\partial\Lambda}{\partial T} + \frac{1}{\eta eff}\frac{\partial\eta eff}{\partial T}\right]\Delta T \qquad (5)$$

$$\frac{\Delta\lambda B}{\lambda B} = (1 - Pe)\Delta\varepsilon + (\alpha + \xi)\,\Delta T \qquad (6)$$

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Where Pe is the strain coefficient, $\Delta\varepsilon$ is the change in strain, ΔT is the temperature change, and α represents the fiber's thermal expansion coefficient and ξ is the thermo-optic coefficient, respectively.

8. Fibre Brag Grating Sensor (FBG) Experimental Setup

Machine vibration can be caused by a variety of factors, including bearings, gears, unbalance, and so on, and even small amplitudes can have a significant impact on overall machine vibration. In this paper, we have chosen an electric motor as a machine and its vibration can be measured with the help of an FBG sensor. The FBG is mounted on the surface of the structure and the vibration takes place due to the variation speed of the motor. The reference Piezo electric-type vibration sensor is used for calibration purposes. The proposed model for the vibration measurement is shown in Figure 3. Due to the vibration of the machines, the wavelength λ_B is continuously changed and captured by the cutting-edge Ibsen I-MON high-speed FBG Interrogator. The real-time signals are acquired by interfacing with the National Instruments LabVIEW environment with FBG Interrogator. Figure 4 portrays the experimental setup of the proposed vibration sensing procedure [13, 15]. Finally, signal processing is used to process the data to get a precise response. The source of vibration has its characteristic frequency, which can be discrete or sum and/or difference frequency. There are three types of vibration measurements: Detection, diagnosis, and prognosis. The simplest form of vibration measurement is used for sensing, where the overall vibration level is measured over a broadband such as 10-1000 Hz or 10-10000 Hz. For machines with little vibration other than bearing vibration, spikes in the vibration signal indicated by crest factor (Peak/RMS) indicate incipient failure, while high energy levels indicated by RMS level indicate critical failure. Defect-free rolling bearings generate very little vibration, while defects cause high natural frequencies. Raceway fracturing is usually dominated by impulsive events at raceway passing frequencies, resulting in a narrow band frequency spectrum. The characteristic defect frequencies and sidebands likely increase with increasing damage, after which their amplitudes decrease, and broadband noise increases with significant oscillations at the shaft rotation frequency. At slow machine speeds, the bearings produce a low-energy signal that is difficult to detect. Additionally, bearings located in gearboxes can be difficult to monitor due to their high energy.

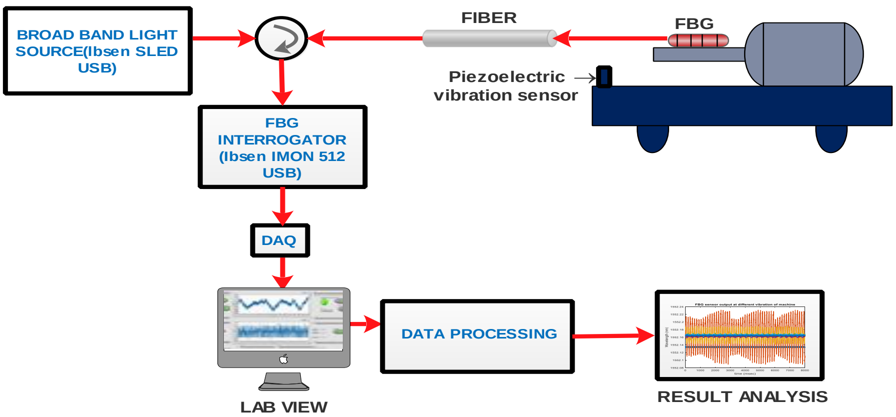

Figure 3: Proposed model for the vibration measurement of a Machine

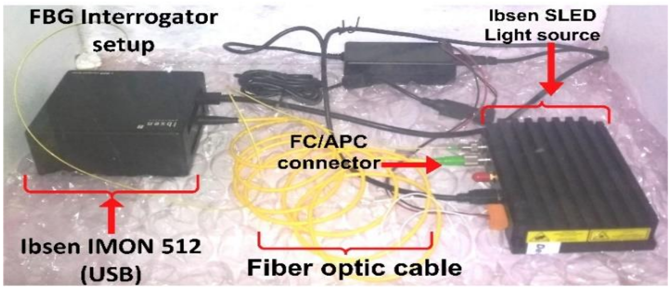

Figure 4: Experimental setup of the vibration sensing procedure

The real-time signal processing scheme is developed and tested at different vibration conditions. The results and analysis section describes the response of the real-time signal analysis scheme adopted in this proposed research work.

9. Results and Discussions

The FBG interrogator is interfaced with a PC to acquire real-time vibration signatures at different points of the structure under test.

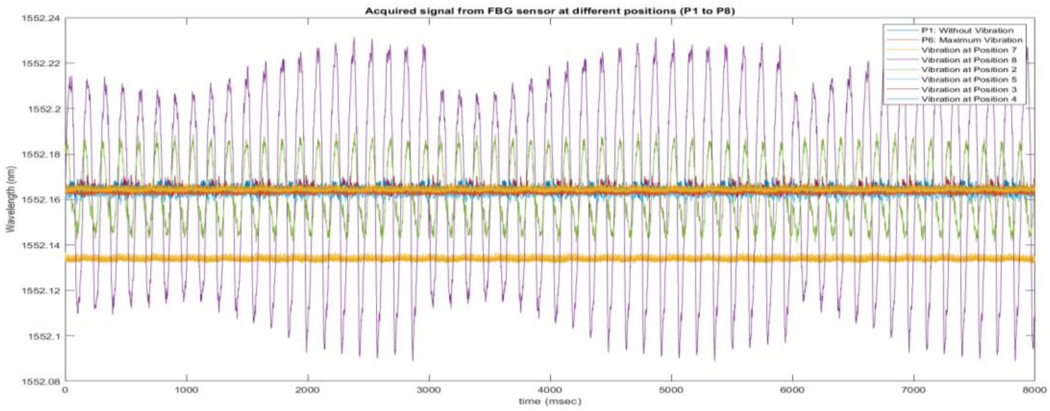

Figure 5: Vibration sensor responses at different points of the structure

Figure 5 shows the vibration response from the FBG sensor element for all the test points on the structure. Further, the signal is conditioned using a moving average filtering method. This is required to nullify the effect of noisy signatures from the raw FBG signal. The filtered vibration signal of the FBG sensing element at different points on the structure is portrayed in Figure 6.

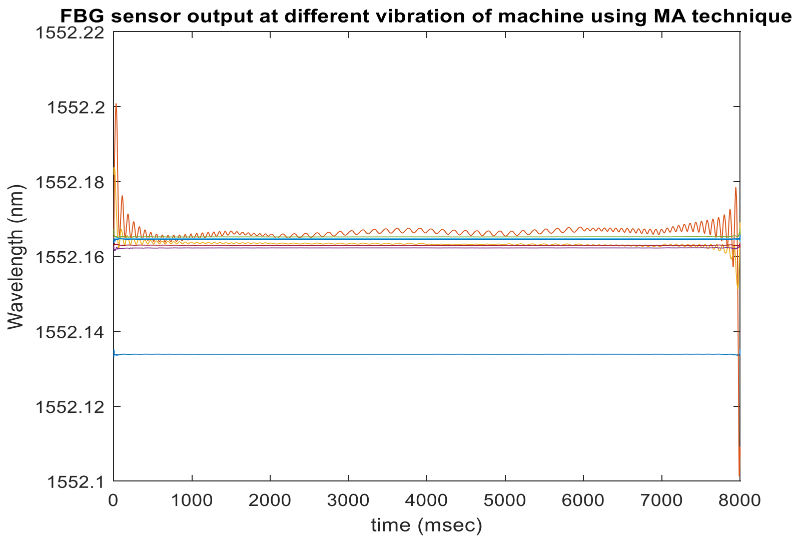

Figure 6: Vibration sensor responses at different points of the structure using the moving average method.

Similarly, the vibration signals at the reference position of the structure are shown in Figure 7. It can be observed that the FBG wavelength varies between 1552.131 nm to 1552.137 nm for no vibration condition. Further, the vibrating motor is configured with a maximum speed of rotation, and the FBG signals are recorded for analysis. Figure 8 shows the FBG signature for maximum vibration at point 6 on the test structure. The peak FBG signature varies from 1552.06 nm to 1552.24 nm at point 6 on the test structure.

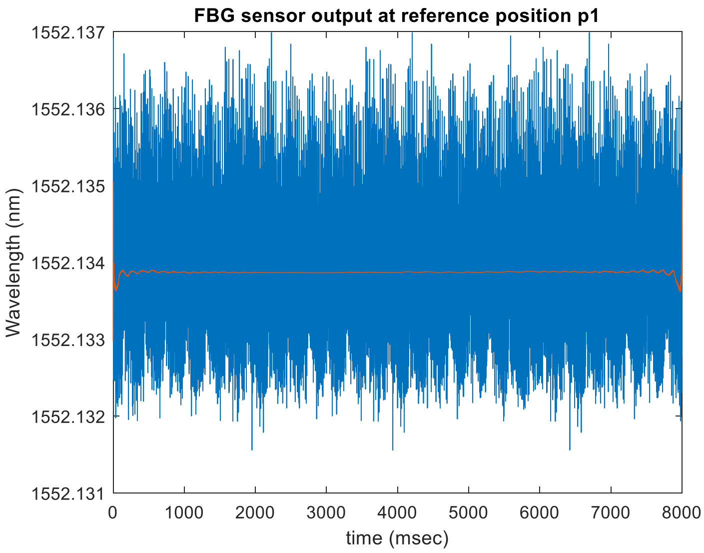

Figure 7: Vibration sensor response at the reference position of the machine

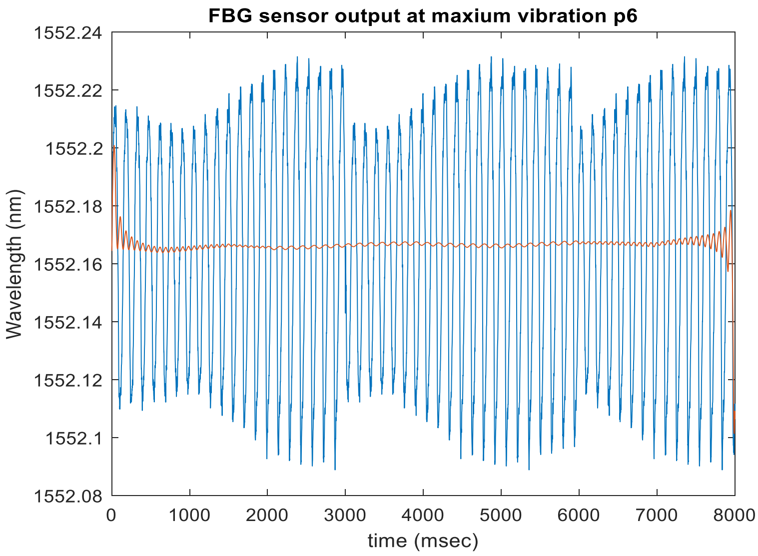

Figure 8: Vibration sensor response during the maximum speed of the machine

Similarly, a similar approach is adapted to measure the vibration signatures at other pre-defined points on the test structure. The frequency response of the time domain response of the FBG sensor is very useful for a further level of vibration analysis. Therefore, every vibration signature is finally converted to a frequency domain representation of the time domain signal using Fast Fourier Transformation (FFT) as in Figure 9. In a similar context, the frequency domain conversion of the maximum vibration is shown in Figure 10.

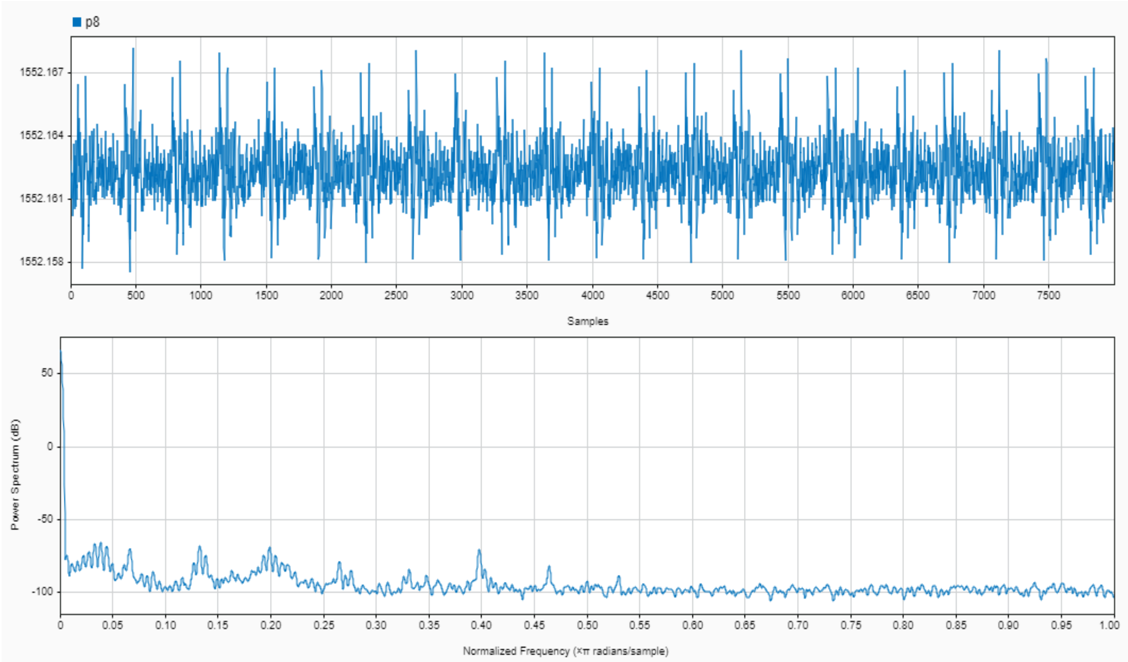

Figure 9: The frequency spectrum of the vibration sensor at the minimum speed of the machine

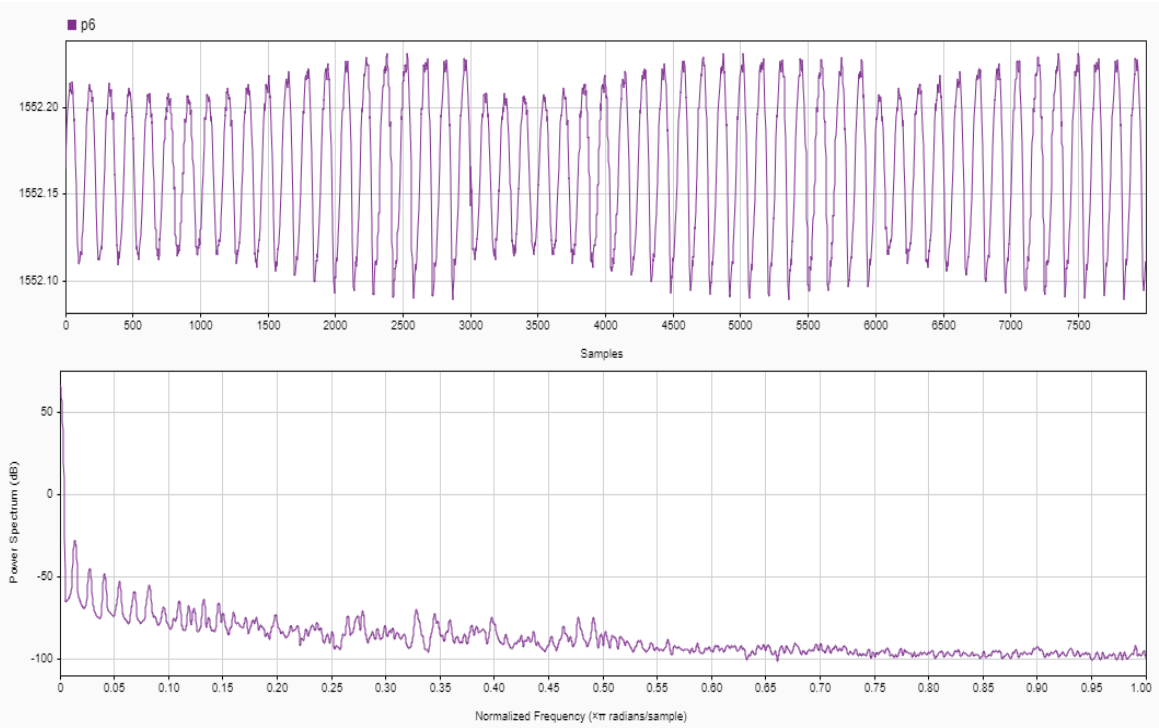

Figure 10: The frequency spectrum of the vibration sensor at the maximum speed of the machine

Table 2: Different wavelength shifts concerning vibration by the rotor

Sl. No.	Test Position	ΔλB (Max & Min) in nm	Power (dB)
1.	P1 (Reference)	1552.133-1552.144	66.8 to -98.3
2.	P2	1552.161-1552.171	66.8 to -98.6
3.	P3	1552.162-1552.165	66.8 to -99.4
4.	P4	1552.163-1552.167	66.8 to -102.0
5.	P5	1552.159-1552.172	66.8 to -101.6
6.	P6	1552.092-1552.231	66.8 to -92.4

7.	P7	1552.143-1552.191	66.8 to -96.9
8.	P8	1552.156-1552.169	66.8 to -97.4

A similar experimental approach is adopted at all the test points and a cumulative analysis is performed by converting the time domain FBG signals to the frequency domain. Table 2 shows different wavelength shifts concerning vibration by the rotor.

10. Proposed Decision Support System Architecture

The FFT-based frequency analysis is well-studied in the results section of the article. The frequency components at different vibration conditions can be stored in a cloud-based distributed platform where long-time monitoring and measurements can be performed. Further, latency in data transmission is also a challenging aspect of this work. Therefore, a pre-processing scheme can be adapted to solve this challenge and the processed information can be sent to the cloud platform in a periodic fashion. The proposed architecture of the DSS integrated with the existing FBG interrogation system is shown in Figure 11. The individual technologies involved in this integrated distributed FBG sensing system are also highlighted in the proposed architecture.

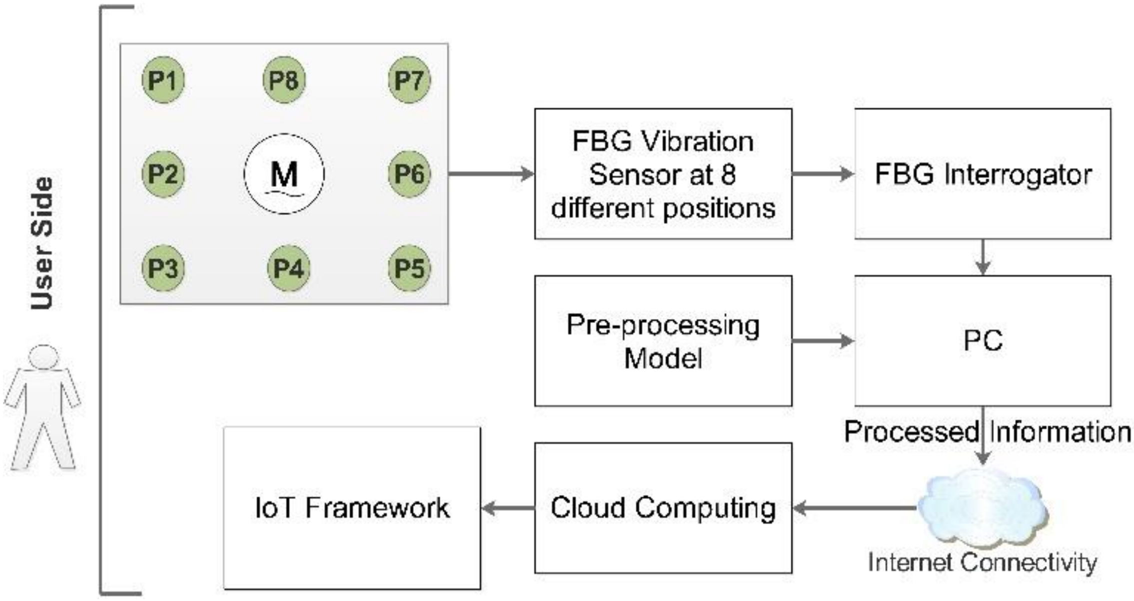

Figure 11: The architecture of the DSS integrated with the existing FBG interrogation system

11. Conclusion

To improve predictive maintenance in industrial operations, Fiber Bragg Grating (FBG) vibration sensors are being integrated into decision support systems, which is a revolutionary approach in the pursuit of operational excellence. By combining cutting-edge technologies, industries are empowered to switch from reactive to proactive asset management, completely changing how equipment is tracked and maintained. The originality of this work lies in the seamless integration of the real-time analytics capabilities of advanced decision support systems with the precision data collection capabilities of FBG sensors. Due to the accurate anomaly detection, predictive modeling, and resource allocation made possible by this synergy, there is less downtime, equipment lasts longer, and there are significant financial savings. This approach turns maintenance practices into a strategic advantage by presenting a thorough methodology that integrates sensor deployment, data analysis, and user interface design. As industries adopt this cutting-edge paradigm, they open the door for more productive, intelligent, and resilient industrial operations and establish new standards for competitiveness and productivity.

Limitations: Although incorporating FBG vibration sensors into decision support systems has enormous potential, difficulties exist due to the high initial cost of sensor deployment, the complexity of algorithm development, and potential data security issues. The effectiveness of the methodology also depends on the accuracy of sensor calibration and the accessibility of historical data.

Future scopes: The focus of future work might be on improving algorithms for more precise anomaly detection and predictive modeling. A more complete picture of the data could be produced by combining FBG sensors with other cutting-edge sensor technologies. Furthering the field's progress towards more resilient, adaptable, and intelligent industrial operations would be the investigation of AI-driven decision support systems and the resolution of scalability issues.

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