Development And Applications of Fiber Bragg Grating Accelerometers

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Abstract. Over the past few years, Fiber Bragg Grating (FBG) accelerometers have seen rapid growth due to their inherent properties, including magnetic immunity and high sensitivity, leading to their increased deployment in environments with extreme conditions or as improved alternatives to traditional sensors. In this article, the development of FBG accelerometers is discussed from three distinct perspectives: low-frequency sensors, high-frequency sensors, and multi-dimensional sensors, highlighting advancements made in recent years. The text also delves into the application domains of such sensors and offers a projection for future developments. It is forecasted that FBG accelerometers will maintain their current trajectory of advancement over the coming years, with more scholars anticipated to propose novel sensor designs based on different structures, either improving upon existing ones or integrating them with other forms of sensing technology. Notably, these sensors are not only expected to find further applications in sectors such as oil exploration and seismic monitoring but are also likely to experience expanded use in aerospace and other specialized domains.

Keywords: Fiber Bragg Grating (FBG) accelerometers; development; prospects.

1. Introduction

The demand for vibration measurement is ubiquitous across a multitude of disciplines, with accelerometers playing an integral role in fulfilling this requirement. The study and development of various accelerometer technologies have been consistently active over the years. Conventional accelerometer types, including piezoelectric and resistive sensors, have long dominated the field due to their established technical maturity and cost-effectiveness. However, since its initial proposal by Willsch Michael and his associates in the year 2000, Fiber Bragg Grating (FBG) accelerometers have experienced a rapid surge in interest and application [1]. Despite the merits of traditional sensors, FBG accelerometers have garnered significant attention from researchers because of their inherent advantages such as magnetic immunity, high sensitivity, and compact size, leading to a proliferation of related studies and an escalating presence in applications under extreme conditions or those demanding heightened sensitivity [2,3].

The design and configuration of FBG accelerometers can be broadly classified into beam-based structures and other alternative designs. Beam-type structures, which are characterized by foundational stability and robustness, have been extensively researched [4]. These efforts have produced numerous innovative variations on the basic beam structure and achieved commendable research outcomes. In contrast, high-frequency sensors predominantly utilize hinge-like configurations [5]. Although these sensors typically exhibit lower sensitivity, resulting in a relatively smaller body of research, there have still been tangible achievements and proven practical capabilities [5].

Despite the prevalence of single-axis sensors, multi-dimensional FBG accelerometers have seen substantial growth in research endeavors in recent times. This expansion has significantly broadened the scope of potential applications for such sensors, enabling them to serve a more diverse array of fields and use cases.

This article aims to provide a comprehensive overview of the development trajectory of FBG accelerometers, categorizing advancements according to low-frequency, high-frequency, and multi-dimensional classifications, while also offering a holistic analysis of contemporary application areas. It is projected that FBG accelerometers will continue to maintain their current growth trend, with a steady increase in associated research and innovation. Given their characteristic lower sensitivity at high frequencies, it is highly plausible that FBG accelerometers will be integrated with other sensor types in future applications, thus enhancing their versatility. Furthermore, they are poised to see extensive adoption and implementation in more specialized sectors such as aerospace and other unique environments in the years ahead.

2. Principle of the FBG Accelerometers

Fiber Bragg Grating (FBG) accelerometer technology operates on the principle of wavelength modulation, where external strain or stress causes a change in the grating period within the FBG [4]. This alteration in the grating's period leads to a shift in the internal refractive index distribution and hence results in a change in the Bragg wavelength [4]. By meticulously tracking these changes in the light wavelength, the strain applied to the FBG can be determined. Subsequently, incorporating the mechanical attributes of the accelerometer, such as mass, stiffness, and damping coefficients, enables the calculation of the object's acceleration [4].

Unlike traditional piezoelectric accelerometers, FBG sensors circumvent electrical isolation challenges, and they are characterized by their diminutive size, lightweight nature, and high sensitivity [6]. These features have facilitated their widespread adoption across various domains including civil engineering, materials science, mechanical engineering and much more [3,7].

3. Technological Development of FBG Accelerometers

Since the inception in the year 2000, Fiber Bragg Grating (FBG) accelerometers have emerged as a relatively novel class of accelerometers that has undergone significant development over the past two decades [1]. These sensors have seen substantial advancements in design refinement, sensitivity enhancement, and broader application scopes.

There has been a notable surge in the number of research publications focusing on Fiber Bragg Grating accelerometers from 2019 through 2023, as evidenced by Figure 1 [8]. This upward trend signifies that the research domain of FBG accelerometers is ripe for further development under favorable conditions. Therefore, it is highly pertinent to consolidate the advancements made in this technology thus far and anticipate its future directions. This paper systematically reviews the recent developments in FBG accelerometers, focusing on three main aspects: low-frequency sensors, high-frequency sensors, and multi-dimensional sensors.

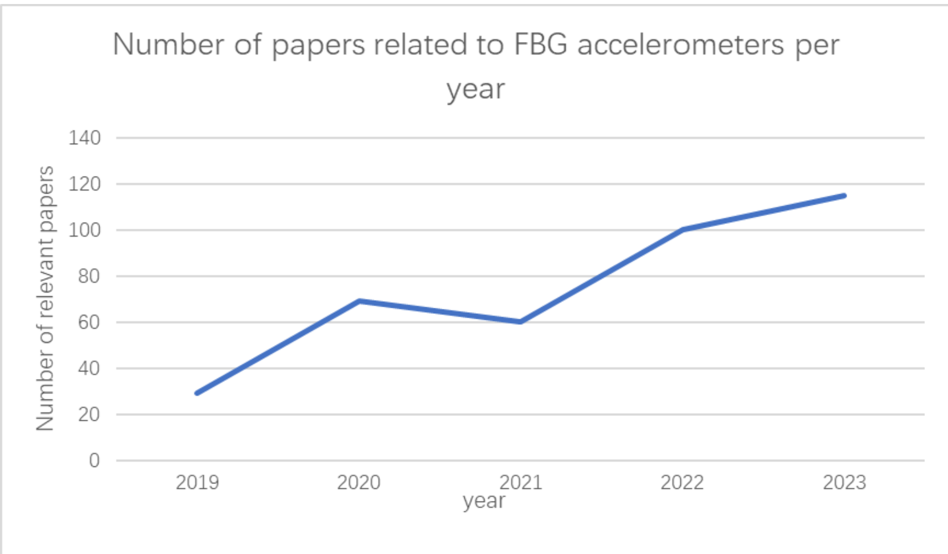

Fig. 1 Number of papers related to FBG accelerometers per year [8]

3.1. Low-Frequency Accelerometers

Cantilever beam-based sensors, which utilize beam structures as elastic components, have garnered extensive interest due to their inherent advantages such as minimal deformation and robust structural simplicity [4]. An exemplar of this category is the sensor designed by Li et al. in 2023, specifically tailored for rotating cantilever systems and operating within a frequency range of 1 to 55 Hz, with a notable sensitivity of 1127.2 pm/g and cross-axis interference less than 5.45% [9]. Concurrently, Qian et al. addressed the issue of low sensitivity in bridge monitoring with a novel FBG accelerometer based on an isostatically designed cantilever structure in 2024 [10]. This sensor achieved a maximum working frequency of 34 Hz and an impressive sensitivity of 664.53 pm/g, accompanied by a linearity of 99.9%, showcasing strong resistance against cross-axis disturbances [10]. Additionally, there are various studies utilizing L-shaped, and F-shaped structures as elastic elements, all demonstrating practical applications [11,12]. Moreover, numerous research endeavors have focused on refining existing beam-type sensors or providing further theoretical substantiation and verification.

Overall, research related to beam-type sensors is the most extensive and has experienced the fastest development, thereby representing a highly active and trending area of advancement in the field.

In recent years, there has also been a substantial amount of research on sensors based on alternative structural configurations, such as those employing springs as diaphragm-based designs, and other innovative structures [13]. While these studies may not necessarily exhibit pronounced advantages over beam-type sensors, they have indeed introduced valuable insights for future developments. For instance, in 2023, Fan et al. addressed the issue of inadequate low-frequency measurement capabilities in large-scale structures by proposing a novel temperature-compensated FBG sensor utilizing a double-arched beam design, as depicted in Figure 2 [14]. In this configuration, two arched beams along with a rectangular component form a vibratory structure, whereupon application of inertial forces from either side of the arches results in deformation of the structure, which in turn induces deformation of the fiber Bragg grating (FBG) sensor situated within the cavity, thereby enabling the measurement of acceleration. Similar to many investigations involving unconventional structures, despite achieving a sensitivity of 1158.6 pm/g that is not particularly outstanding, the sensor's simple design and attainment of the required sensitivity serve as a promising conceptual framework and experimental validation for future designs.

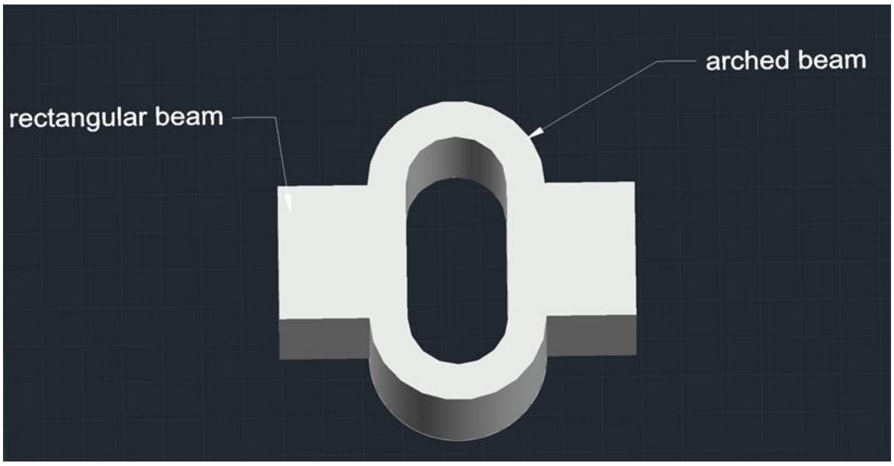

Fig. 2 N Double-arched beam structure [14]

The growing preference for FBG accelerometers in low-frequency sensing applications stems from their superior sensitivity compared to other types, particularly piezoelectric accelerometers, when high sensitivity at low frequencies is crucial. Furthermore, FBG accelerometers' inherent insensitivity to electromagnetic interference (EMI) gives them a distinct advantage, leading to widespread adoption.

3.2. High-Frequency Accelerometers

High-frequency FBG accelerometers often employ circular or elliptical hinges due to their ability to tailor the detection frequency of the sensor according to specific requirements [15]. Presently, research in the high-frequency domain is relatively scarce because such sensors tend to exhibit decreasing sensitivity as the frequency increases, which leads to the preference for other types of sensors in most scenarios [5]. However, these sensors hold inherent value in research due to their electromagnetic interference (EMI) immunity properties that allow them to function effectively in environments with strong electric fields and magnetic fields.

For instance, Zhang Haoran in 2023 designed a symmetrical FBG accelerometer where bearings and flexible hinges were used to connect two masses, as shown in Figure 3 [5]. The central asymmetric structure serves as a flexible hinge, while the cylindrical elements on both upper and lower sides house the FBG accelerometers; the round cavities on the left and right sides accommodate bearings that facilitate rotation of the system. This design aimed to mitigate the issue of lower structural precision in conventional configurations. Experimental results demonstrated that the sensitivity of this novel sensor could be doubled compared to its predecessors, although it still presented certain challenges, such as not meeting the demands for portable installations [5]. Nonetheless, the device has reached a stage ripe for broader application.

This case illustrates that there is indeed development potential for this type of sensor in the high-frequency direction, despite the inherent characteristics that might make research and application challenging. In fact, there have been tangible advancements in this area, demonstrating that despite the limitations, these sensors can offer valuable contributions and are not inherently prohibitive for further study and practical use.

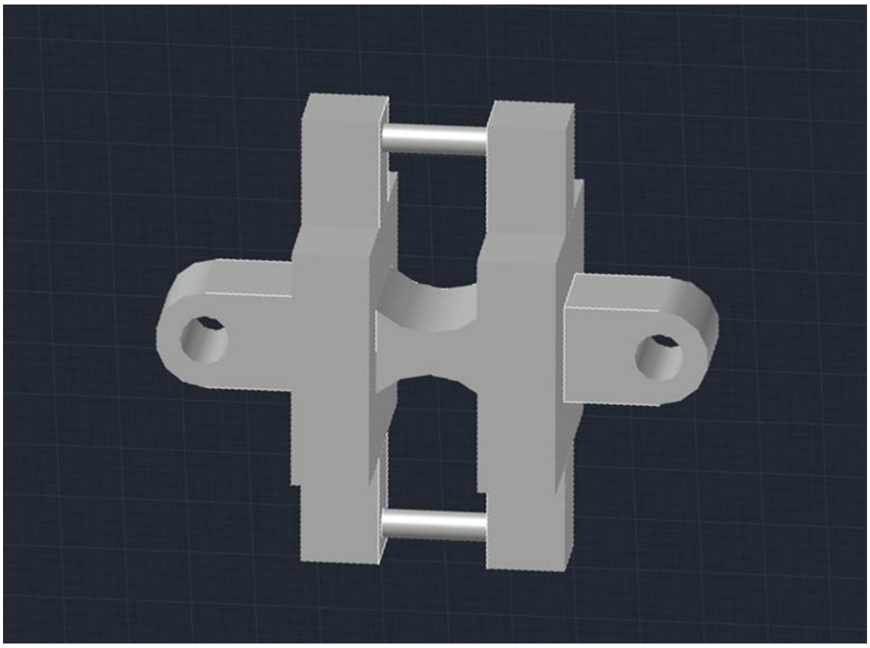

Fig. 3 A hinge-based high-frequency Fiber Bragg Grating accelerometer structure [5]

3.3. Multi-Dimensional Accelerometers

The majority of FBG sensor studies focus on one-dimensional sensing capabilities, which are insufficient for complex scenarios involving transverse forces surpassing axial forces [16]. Consequently, researchers have ventured into the development of two- or three-dimensional sensors suitable for broader application contexts. For example, Guo Yongxing and colleagues proposed an integrated FBG-based triaxial accelerometer utilizing a cross-shaped elastic element [16]. With merely five sensors, they achieved three-dimensional measurement along with temperature compensation. This innovative design boasts a high operating frequency, excellent linear measurement capability, and efficient temperature compensation, with sensitivities of 1.36 pm/g, 1.70

pm/g, and 1.31 pm/g in the x, y, and z directions, respectively. Once packaged, this sensor becomes suitable for practical applications. This category of research has seen a gradual increase in recent years, with the majority of studies holding practical significance and yielding valuable outcomes. It is fair to consider this as an important and emerging trend.

3.4. Additional Advances

In recent years, several lines of research aimed at enhancing sensor precision through the use of improved temperature compensation mechanisms and other methods [17]. Other studies concentrate on augmenting the corrosion resistance, cold and heat tolerance properties of the sensors to meet the stringent demands of specialized environments like radio telescopes and oil exploration [18,19]. Moreover, there is a dedicated research thrust towards miniaturizing sensors to facilitate their deployment in seismic exploration, deep well inspection, and similar challenging settings. These advancements contribute significantly to broadening the scope and functionality of FBG accelerometers across various domains.

4. Application Research of Fiber Bragg Grating Accelerometers

Low-frequency FBG, due to their high sensitivity characteristics, have increasingly replaced traditional sensors with lower sensitivity in applications such as seismic monitoring, structural detection, and oil exploration over the past few years, witnessing widespread usage [3,20,21]. Conversely, high-frequency sensors are more commonly employed in areas like vibration monitoring on high-speed trains and microseismic surveillance [22,23].

A common application trend for both types is the growing use of these sensors in environments characterized by strong magnetic fields, high pressures, and so forth, including magnetic levitation trains, oil and gas exploration, and earthquake monitoring. This shift is driven by the inadequacies of prior sensor technologies, which often suffer from electromagnetic interference susceptibility, difficulty in miniaturization, poor flexibility, low corrosion resistance, and complex wiring, among other limitations [5,24]. To enhance sensitivity and improve operational conditions, fiber Bragg grating (FBG) accelerometers that excel in these aspects have been chosen for many applications. Several studies have investigated the potential use of FBG sensors in these contexts. For instance, Wei Shiming et al. examined the dynamic equation of a cantilever-based FBG sensor under wave action, demonstrating its capability for precise measurements of internal parameters within rock masses [3].

5. Future Development Directions and Application Prospects of Fiber Bragg Grating Accelerometers

5.1. Future Development Directions

The rapid advancement of Fiber Bragg Grating accelerometers suggests several possible future directions:

Enhanced Beam-Structured Sensors: The popularity of beam-based sensors as a common elastic component persists, with ongoing research into various beam-type configurations. New designs may be proposed, while studies aiming to refine existing beam-style sensors are likely to continue in the coming years.

Diverse Structural Configurations: There will be an increased proposal of FBG accelerometers featuring different structural forms, expanding the range of sensor design options.

Novel Hinge-Based High-Frequency Sensors: More high-frequency FBG accelerometers employing innovative hinge structures can be expected. As the diversity of sensor types increases, so will the number of studies dedicated to optimizing existing sensors or evaluating their performance characteristics.

Hybridization with Other Sensor Types: Presently, research integrating FBG sensors with other sensor technologies to achieve better results is relatively limited. Given that FBG sensors boast advantages like EMI immunity and compact size but face limitations in high-frequency sensing, future studies will probably explore ways to combine them effectively with other types of sensors to optimize overall functionality.

Multi-Dimensional Sensors: Research on multidimensional fiber Bragg grating accelerometers, while relatively sparse in the past, has seen a recent increase with more scholars gradually transitioning from two-dimensional to three-dimensional investigations over the last few years. This trend indicates a proliferation of related studies, and it is evident that multidimensional sensors are capable of accommodating a broader range of application scenarios. Consequently, there is a likelihood that future research will involve a greater number of scholars delving into the development of multidimensional sensors.

5.2. Application Prospects

The application of fiber Bragg grating (FBG) sensors has been rapidly expanding, finding broad utilization in domains such as aerospace engineering, structural health monitoring, and seismology. This is due to their inherent high sensitivity and robust resistance to electromagnetic interference, which renders them suitable for applications demanding heightened sensitivity and operation in special environmental conditions. As the research's progresses leading to the continuous development of FBG accelerometer technology, it is anticipated that more traditional sensors like piezoelectric and resistive types will be supplanted by FBG sensors. These advanced sensors are expected to see increased use in scenarios necessitating high sensitivity and specialized environments, not limited to previously mentioned examples but also encompassing tasks like detecting soil liquefaction during earthquakes. Earthquake-induced ground vibrations typically have a period above one second, corresponding to low frequencies, which suits the deployment of FBG accelerometers. Moreover, the severe impact of soil liquefaction on foundations and structures underscores the need for detection.

Furthermore, the advent of multidimensional FBG sensors, coupled with the introduction of diverse sensor designs and technological refinements, allows these sensors to accommodate complex situations at lower costs. For example, in the aerospace sector, where measurements of acceleration often involve intricate directional and magnitude variations and require high precision under stringent conditions, FBG accelerometers could potentially play a more substantial role in the future.

6. Summary

Fiber Bragg Grating (FBG) accelerometers, as a relatively new and less historically developed accelerometer technology, have gained considerable traction in recent research with the concomitant emergence of several practical applications. This paper initially examines the current state of technological development for FBG accelerometers, noting that low-frequency sensors based on beam structures have seen rapid advancement over the past few years, with continuous improvements proposed by scholars and the introduction of novel types. Although high-frequency FBG accelerometers have experienced fewer studies, they nonetheless demonstrate practical utility and have made significant strides forward. The advent of multi-dimensional sensors has augmented the versatility of FBG accelerometers, enabling their use across a broader range of environments.

Subsequently, this paper delves into the application domains of FBG accelerometers, observing that due to their inherent characteristics, these sensors are rapidly evolving for use in demanding conditions and have supplanted certain traditional accelerometer technologies in some instances.

Regarding future prospects, this study posits that overall, FBG accelerometers exhibit a promising trend in development with technology continuously refining. It is envisioned that in the future, these sensors will find wider application in more specialized fields, achieving further technical advancements. Moreover, there is a likelihood of integration with other sensor types, resulting in complementary functionality that capitalizes on the unique attributes of FBG accelerometers.

In summary, this paper presents a comprehensive discussion of various aspects concerning FBG accelerometers, summarizing the present state of development and providing a concise forecast of the technology's future trajectory. This work offers valuable insight into the progression and potential future directions of FBG accelerometer technology.

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