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String-type based two-dimensional fiber bragg grating vibration sensing principle and structure optimization

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ABSTRACT

Vibration is a common phenomenon in the field of engineering, and it typically carries affluent and essential faulty information on health conditions of measured targets. Consequently, it is crucial to ensure safe and stable operations of engineering equipment through the use of effective vibration detection technologies. The increasingly and extensively advanced requirements for vibration detection make it essential to realize real-time multi-dimensional vibration information. To this end, a string-type two-dimensional (2D) fiber Bragg grating (FBG) vibration sensor has been presented through the use of both axial and transverse properties of a tightly suspended optical fiber. This sensor employs a novel mass block structure that possesses a specially designed hole pattern and introduces two stiffening beams through them to enhance the dynamic properties and remove the coupled rotational interference. The sensing principle and the proposed guidelines of cross-interference elimination have been validated by the simulation and experimental results. With the configuration of two stiffening beams, the working bandwidth of the proposed sensor has been enlarged to be respectively 10–150 Hz and 10–800 Hz along the *x* and *y* direction, which were consistent with both theoretical and simulation results. The rotational interference in the *x* direction has been significantly reduced to 15.3%. However, its complete removal requires a strict fabrication requirement and a bulky sensor size for this design. To further remove the interference and make the sensor compact, an optimized mass structure has been proposed to achieve almost complete removal of the rotational interference in the *x* direction.

1. Introduction

Vibration is a significantly important physical quantity in the field of engineering monitoring, and it typically contains various faulty features. To ensure safe and stable operations of engineering equipment, extensive efforts have been made to develop effective vibration detection technologies. Traditional electrical sensing techniques such as, micro-electromechanical systems (MEMS) and piezoelectric vibration sensors, have been developed to detect vibrational signals [1]. However, these sensors are susceptible to electromagnetic (EM) interferences and difficult to support the implementation of distributed measurements. These limitations make it challenging for these sensors to operate stably in the high-intensity EM environment field and satisfy the requirement of simultaneous multi-point vibration detection.

In contrast, FBG-based sensors have been increasingly and extensively used in the field of engineering owing to their remarkable advantages such as, miniature size, immunity of EM interference and easy implementation of distributed measurements [2,3]. Consequently, many kinds of FBG-enabled vibration sensors have been designed based on these excellent attributes [4–7,9–11]. The basic principle of the most commonly used FBG-based vibration sensors typically involves pasting FBG elements on cantilevered-beam structures and other improved beam forms to sense the dynamic strains on the elastomer surface for vibration measurements [4–7], as shown in Fig. 1a). However, such sensors suffer from the drawbacks associated with the pasting procedure such as, a low repeatability and chirping failure. These shortcomings are caused by the inconsistent manual operations and the non-uniform strain distribution on the elastomer surface [8]. To overcome these limitations, the axial property of a suspended optical fiber has been investigated to avoid the pasting process. If the inertia force is directly exerted on the fiber along the axial direction [9–11], as shown in Fig. 1b), the accompanied drawbacks of the pasted FBG vibration sensors can be overcome.

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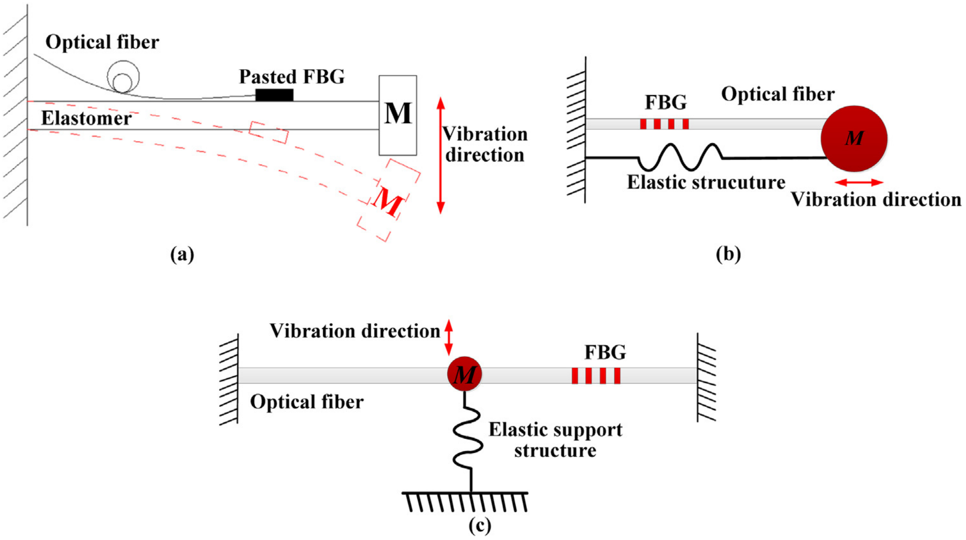

Fig. 1. Different configurations of FBG-based vibration sensors: (a) Pasted FBG based vibration sensor; (b) FBG vibration sensors based on the axial property of a suspended optical fiber; (c) FBG vibration sensor based on the transverse property of a suspended optical fiber.

However, vibration is a multi-dimensional spatial vector. The above-mentioned FBG-based vibration sensors are only able to detect 1D vibration, failing to meet the requirements of detecting multi-directional vibration. Thus, researchers also have explored other designs based on FBGs to achieve multi-dimensional vibration detection. Guo et al. designed a 2D vibration sensor that pasted four FBGs on a stainless steel tube along the circumference with an interval of 90°[12]. However, the working principle of this sensor was still based on the pasted FBG to measure vibration. Therefore, this design experienced the same drawbacks with the previously proposed vibration sensors in [4–7]. Antunes et al. also proposed a biaxial FBG accelerometer based on the axial property of optical fiber. Four FBGs were separately cross-linked on the top surfaces of the mass blocks [13]. When the mass vibrated along the main axis direction (*x* or *y*), it could induce the elongation of one FBG and the compression of the other one located at the opposite position. The corresponding vibration can be determined through the use of differential operation on center wavelength shifts from the two opposite FBGs. The sensitivities were respectively 87.848 pm/g and 92.351 pm/g for each sensitive direction. However, this design did not take the cross interference induced by the transverse direction into consideration. 3D FBG-enabled vibration detection sensors have also been implemented by using the same measurement and decoupling principle in each direction [14–17]. These sensors extended the design in [13] by adding an optical fiber inscribed with a pair of FBGs on the both up and down surfaces of the mass block in [14–17] to detect the *z*-direction vibration. However, the drawbacks associated with the proposed design were that the sensor structure was bulky with six FBGs, and suffered from limited sensitivity. The fiber was also easily broken under a large transverse impact loading. To address these issues, a 2D FBG vibration sensor with a higher sensitivity has been presented based on both of the axial and transverse properties of a suspended optical fiber in our previous work [18]. This design used two FBGs to achieve 2D vibration measurement and make the sensor package compact. The addition and subtraction operations on FBGs' center wavelength shifts have been implemented to decouple the vibration into two directions. However, the implementation suffers from a small working bandwidth and experiences a large cross interference of up to 64.65% in the *x* direction.

To overcome the limitations in our previous work [18], a novel mass block structure has been proposed with a specially designed hole pattern and the introduction of two stiffening beams through them. The hole pattern consists of 3 through holes, and the suspended optical fiber inscribed with two FBGs goes through the central one and is fixed with it. The introduced two stiffening beams are configured with a symmetrically parallel arrangement on both sides of the suspended optical fiber to go through the remaining two holes. This design improves the resonant frequency and enlarges the working bandwidth. This implementation also significantly reduces the cross inference in the *x* direction, and further decreases the interference in the *y* direction. However, the complete removal of the cross inference in the *x* direction require a bulky sensor size and ideal fabrication. To further solve these issues, an optimized structure has been proposed to achieve almost complete removal of the interference in the *x* direction. The effectiveness of this optimized structure has been validated by both of theoretical and experimental analysis. This paper is organized as the following sections: working principle and sensor structure design, simulation analysis of the proposed sensor, experiments and structure improvement, and conclusion.

2. Working principle and sensor structure design

2.1. Sensing principle for 2-D vibration detection

The sensing principle of FBG-based multi-dimensional vibration detection can be mainly categorized into two types on the basis of the decoupled mode (refer to Fig. 2). The first category typically involves developing decoupling algorithms based on wavelength and phase demodulation, to separate the resultant responses into three decoupled signals that are corresponding to each direction (Fig. 2a). Instead, the second type introduces the novel sensor mechanical designs with physical constraints for decoupling vibration signals, and typically uses three FBGs to measure 3D vibration with each one detecting one vibration direction (Fig. 2b). The second method was selected to design the 2D vibration sensor in this work, which can easily achieve the decoupling vibration measurement.

The proposed 2D FBG vibration in our previous work [18] only considered the three translational degrees of freedom (DOFs) along the *x*/*y*/*z* direction. This design neglected the influences from the other three rotational DOFs of the mass block (Fig. 3), resulting in a large cross interference of 64.65% in the *x* direction. To improve