Fiber Bragg grating based acceleration sensors: a review

Yongxing Guo
Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education, Wuhan University of Science and Technology, Wuhan, China and Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, China

Min Chen
Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education, Wuhan University of Science and Technology, Wuhan, China

Li Xiong
Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education, Wuhan University of Science and Technology, Wuhan, China and Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, China

Xinglin Zhou
Key Laboratory of Metallurgical Equipment and Control Technology, Ministry of Education, Wuhan University of Science and Technology, Wuhan, China, and

Cong Li
Hubei Key Laboratory of Mechanical Transmission and Manufacturing Engineering, Wuhan University of Science and Technology, Wuhan, China

Abstract

Purpose – The purpose of this study is to present the state of the art for fiber Bragg grating (FBG) acceleration sensing technologies from two aspects: the principle of the measurement dimension and the principle of the sensing configuration. Some commercial sensors have also been introduced and future work in this field has also been discussed. This paper could provide an important reference for the research community.

Design/methodology/approach – This review is to present the state of the art for FBG acceleration sensing technologies from two aspects: the principle of the measurement dimension (one-dimension and multi-dimension) and the principle of the sensing configuration (beam type, radial vibration type, axial vibration type and other composite structures).

Findings – The current research on developing FBG acceleration sensors is mainly focused on the sensing method, the construction and design of the elastic structure and the design of a new information detection method. This paper hypothesizes that in the future, the following research trends will be strengthened: common single-mode fiber grating of the low cost and high utilization rate; high sensitivity and strength special fiber grating; multi-core fiber grating for measuring single-parameter multi-dimensional information or multi-parameter information; demodulating equipment of low cost, small volume and high sampling frequency.

Originality/value – The principle of the measurement dimension and principle of the sensing configuration for FBG acceleration sensors have been introduced, which could provide an important reference for the research community.

Keywords Fiber Bragg grating, Acceleration sensor, FBG accelerometer, Fiber optic sensor

Paper type Literature review

1. Introduction

Basically, all things are inseparable from vibration, so vibration monitoring is of great significance. Pre-warning and forecast can be realized by judging the activity regularity of potential geological hazards in the fields of geological prospecting, oil reservoirs and coal mines through micro-vibration monitoring (Gautam *et al.*, 2019; Kamenev *et al.*, 2016; Wang *et al.*, 2016). The loss caused by equipment failure can be reduced by means of automatic online monitoring (Chen *et al.*, 2019). Then the

The current issue and full text archive of this journal is available on Emerald Insight at: **https://www.emerald.com/insight/0260-2288.htm**

Sensor Review

[DOI 10.1108/SR-10-2020-0243]

This work was supported in part by the National Natural Science Foundation of China under Grant 52075397 and in part by the National Major Scientific Instruments Development Project of China under Grant 51827812 and in part by the Open Projects Foundation of Yangtze Optical Fiber and Cable Joint Stock Limited Company (YOFC) under Grant SKLD1908.

Received 23 October 2020
Revised 30 December 2020
Accepted 15 January 2021

significance of vibration monitoring in the fields are very obvious, such as perimeter protection, railway, ship, biomedical, aeronautics and astronautics. However, in allusion to some special occasions, such as the strong electromagnetic interference inside the electrical equipment (Dreyer *et al.*, 2018), chemical corrosion in oil reservoirs (Rong and Qiao, 2019) and long-distance signal transmission (Nan *et al.*, 2019), the traditional accelerometers in the form of capacitance and piezoelectric can no longer meet the market needs. Therefore, it is imperative to develop high-performance acceleration sensors with electromagnetic interference resistance, corrosion resistance, high sensitivity and long-distance signal transmission.

The fiber Bragg grating (FBG)-based sensor has been widely recognized in recent decades. In addition to these advantages of electromagnetic interference resistance, corrosion resistance, small volume, the light weight of optical fiber sensor (Zhang *et al.*, 2019; Fu *et al.*, 2019), FBG sensors have sensing signals which not affected by the intensity of the light source, the loss of the optical fiber and the polarization of light interference, the strongly multiplexing capabilities and easily form various kinds of fiber sensing networks to realize distributed multi-point measurement (Xiong *et al.*, 2020; Sahota *et al.*, 2020; Guo *et al.*, 2019).

Besides the environmental adaptability, the resonant frequency, sensitivity, measurement range and accuracy of the sensor are also important indicators to measure the property of the sensor. Piezoelectric, piezoresistive and capacitive accelerometers have resonant frequencies of tens of thousands of hertz due to their material and structure characteristics. Piezoelectric acceleration sensor has many advantages, such as low cost, availability in many forms and simplicity in handling and implementation but it also has the problems of low linearity and measurement accuracy caused by external excitation and piezoelectric material (Shivashankar and Gopalakrishnan, 2020; Pramanik and Arockiarajan, 2019). Capacitive acceleration sensor has the advantages of high sensitivity, zero frequency response and wide dynamic range, but it is easy to be interfered by the outside world and only suitable for low-frequency fields, such as seismic detection and geological exploration (Alessandro *et al.*, 2019; Giacci *et al.*, 2017). Piezoresistive acceleration sensor has the advantages of small volume, low output impedance and high measurement accuracy, but it is easily affected by temperature (Kordas and Pitkanen, 2019; Liu *et al.*, 2018). Unlike the above sensors, the resonant frequency of the current FBG accelerometer can only reach a few kilohertz. However, in the working frequency band, its measurement accuracy is high, the acceleration measurement range is large (Guo *et al.*, 2019), the linearity is greater than 0.98 and the sensitivity can be improved by changing the sensitive structure. Moreover, it is suitable for the vibration measurement of low-medium frequency and high sensitivity. FBG acceleration sensor has excellent environmental adaptability and working performance and it can measure the frequency, phase, amplitude and other information that cannot be measured by the vibration sensor. Therefore, the FBG acceleration sensor has been widely used in the field of vibration measurement in recent years.

This paper introduces the research status of FBG acceleration sensors across the world in recent 10 years depending on the acceleration measurement dimensions and summarizes the design methods, working principles and structural characteristics of various types of sensors. Finally, some commercial sensors are introduced and the development trend is prospected.

2. Measurement principle of fiber Bragg grating acceleration sensor

2.1 Sensing principle of fiber Bragg grating

The sensing principle of FBG is shown in Figure 1. FBG is a periodic modulation of the index of refraction in the core of an optical fiber. When a broadband light transmits along with the fiber core, the FBG reflects a narrowband portion with a specific wavelength, while the rest portion of the broadband light passes through. The center wavelength of the reflection spectrum is defined as λ_B, which can be represented by two parameters (Wang *et al.*, 2018a, 2018b):

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the optical fiber, Λ is the periodicity of the grating.

The wavelength shift of λ_B is decided by the changes of n_{eff} and Λ, which are mainly influenced by the axial strain $\Delta\varepsilon$ and environment temperature ΔT. In this case, the Bragg wavelength dependency on the strain and temperature could be described by Guo *et al.* (2020):

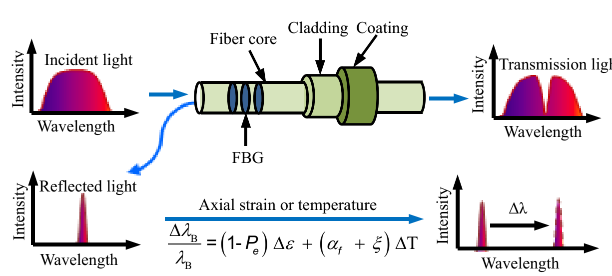
$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\Delta\varepsilon + (\alpha_f + \xi)\Delta T \tag{2}$$

where α_f is the thermal expansion coefficient, ξ is the thermal-optic coefficient and P_e is the elasto-optical coefficient.

2.2 Measurement principle of acceleration sensor

According to the formula in the above section, the fiber Bragg grating can sense the change of strain and temperature, so the FBG acceleration sensor can use the wavelength, intensity and spectral bandwidth modulation principles of the grating to detect the external acceleration. Full encapsulation and two-point encapsulation are the main encapsulation forms of FBG acceleration sensors. When the full encapsulation method is used, FBG is usually attached to the surfaces of sensing structures, such as the beam and elastic tube structure. When a two-point encapsulation method is used, two ends of the pre-stretched optical fiber with FBG are usually fixed between the matrix and the inertial object connected with the sensing structures, such as the beam, elastic tube, elastic diaphragm

Figure 1 Schematic diagram of the FBG-based sensing principle



and elastic shell structure. Or the optical fiber is directly used as the sensing structure. When the external vibration occurs, the internal sensitive structure of the acceleration sensor will change with corresponding displacement or strain, which causes the wavelength of the FBG to drift. The wavelength drift of the FBG is modulated and demodulated to the output wavelength, light intensity and bandwidth information by the corresponding FBG wavelength, intensity and spectral bandwidth sensing system. After the sensitivity calibration experiment, the external acceleration can be obtained by the output information change of the system. The principle block diagram is shown in Figure 2.

3. Fiber Bragg grating-based one-dimensional acceleration sensor

At present, the FBG-based one-dimensional acceleration sensor is the most studied one by global scholars and the measurement of vibration in a single direction makes the design of the structure rich and diverse. To meet the requirements of the sensitivity and resonant frequency of the sensor in different fields, researchers designed a series of FBG acceleration sensors from the aspects of FBG bonding mode, the structure of the elastomer where the grating is located and the principle of information detection. According to the principle of information detection and monitoring architecture, the extensive application of FBG-based one-dimensional acceleration sensor in vibration monitoring is summarized and classified, as shown in Figure 3.

Figure 2 Schematic diagram of the principle of FBG-based acceleration sensor

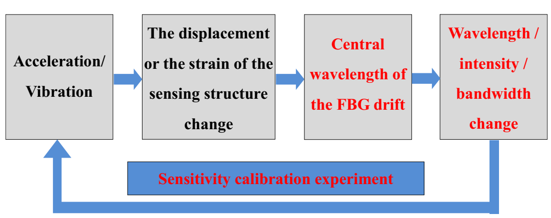
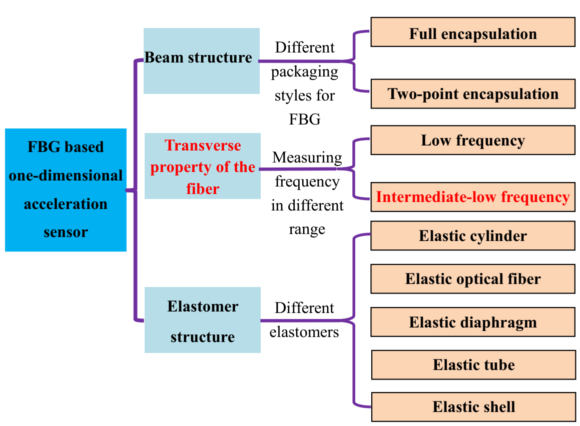


Figure 3 Schematic classification diagram of FBG-based one-dimensional acceleration sensor



3.1 Fiber Bragg grating acceleration sensor based on beam structure

Cantilever beam has the characteristics of simple structure and stable performance, becoming the classic elastic element of the low-frequency vibration FBG sensor (Wang *et al.*, 2015a, 2015b). In this kind of structure, as FBG has two encapsulation modes of complete encapsulation and two-point encapsulation, the performance of this sensor will change with the change of encapsulation mode (Kuang *et al.*, 2018; Xiong *et al.*, 2019). The following will introduce this type of FBG acceleration sensor from different encapsulation modes.

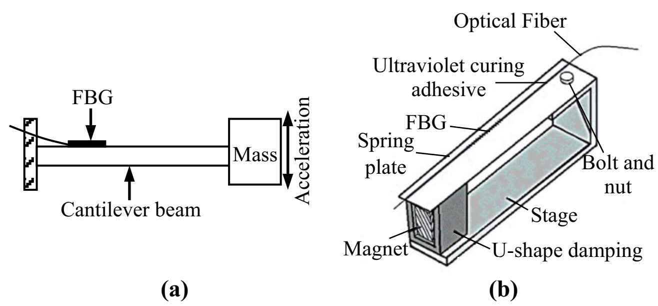
3.1.1 Fully encapsulated fiber Bragg grating

Owing to FBG completely encapsulated and fixed on the beam surface by researchers, when the mass block connected to the cantilever beam vibrates, the grating distance of the FBG will change due to the axial strain of the pasted part. Therefore, based on the principle of wavelength modulation, the central wavelength drift of the FBG measured by the wavelength demodulator can be used to invert the external acceleration information. Figure 4(a) shows the schematic diagram of the wavelength detecting FBG acceleration sensor based on the cantilever beam (Guo, 2013a, 2013b, 2013c; Guo, 2014).

In 2003, Shi *et al.* (Shi *et al.*, 2003) used the cantilever beam structure with equal strength to complete the measurement of the acceleration signal. In 2006, on the basis of the structure designed by Shi *et al.* (2003), Liu *et al.* (2006) put the mass block on a fixed cylindrical rod, which greatly improved the transverse anti-interference ability of the sensor. Compared with the above sensors (Shi *et al.*, 2003; Liu *et al.*, 2006) which only completed preliminary tests in the laboratory, Zhang *et al.* (2017a, 2017b), Yüksel *et al.* (2018) and Zhang *et al.* (2018) designed the acceleration sensors based on traditional cantilever structure for hydraulic pump vibration monitoring (Zhang *et al.*, 2017a, 2017b), railway monitoring (Yüksel *et al.*, 2018) and seismic acquisition (Zhang *et al.*, 2018). From 2019 to 2020, Tiwari *et al.* (2019) and Udos *et al.* (2020) improved the traditional cantilever beam structure and designed the acceleration sensors for structural health monitoring. The former (Tiwari *et al.*, 2019) replaced the traditional triangular and rectangular cantilever beams with the curved cantilever beam and designed a fully encapsulated high-sensitivity sensor for low-frequency vibration measurement. The latter (Udos *et al.*, 2020) combined the traditional cantilever beam structure with the magnetic damper to suppress the resonance and designed an acceleration sensor whose working frequency band was widened. The structure is shown in Figure 4(b). However, the above sensors did not solve the problem of the temperature-strain cross-sensitivity.

FBG can sense the change of temperature and strain at the same time, and if the problem of strain-temperature cross-interference is not solved, the measurement of the acceleration sensor will not be so accurate. In 2009, Nan and Zou (2009) and Jiang *et al.* (2009) proposed the FBG vibration sensors based on the intensity modulation principle and the matching filtering demodulation method. The former (Nan and Zou, 2009) attached the sensing grating to the main beam to detect a change in temperature and vibration and the matched grating to the tunable auxiliary beam to detect a change in temperature. By matching the filtering demodulation method, the difference

Figure 4 Schematic diagram of wavelength detecting FBG-based acceleration sensor based on the cantilever beam structure



Notes: (a) Cantilever beam; (b) cantilever beam - magnet damper

not affected by temperature between two FBG wavelength drifts is converted into the change of light intensity, so the external acceleration information can be obtained by detecting the change of light power and the structure is shown in Figure 5. The latter (Jiang *et al.*, 2009) added electromagnetic damping to a similar structure (Nan and Zou, 2009), greatly increasing the resonant frequency of the sensor.

Relative to the FBG acceleration sensor which needs to set the temperature compensation grating to realize the temperature compensation, Zhou *et al.* glued the FBG diagonally to the outside of the constant strength cantilever beam (Zhou *et al.*, 2009a, 2009b; Zhou *et al.*, 2010) or the simply supported beam (Li *et al.*, 2009; Li *et al.*, 2010) and proposed two temperature-insensitive acceleration sensors based on the spectral bandwidth modulation principle in 2009. When the cantilever beam or the simply supported beam is stimulated by external acceleration, the reflection bandwidth that does not vary with temperature change will vary linearly for the FBG tuned with a chirp. Therefore, the change of acceleration can be calculated by detecting the change of reflection bandwidth. Then the cantilever beam structure is shown in Figure 6.

Although the FBG acceleration sensor based on spectral bandwidth modulation principle is not affected by the strain-temperature cross-sensitivity, the multiplexing ability of this type of sensor is poor and the measurement accuracy is low. From 2018 to 2019, Yao *et al.* (2018) and Yao *et al.* (2019) designed two-wavelength detecting multi-parameter measurement systems which integrated sensor detection and data analysis. In 2018, Yao *et al.* (2018) encapsulated the stress sensing grating on the surface of the measured object and encapsulated the vibration sensing grating on the surface of the elastic steel plate equivalent to the cantilever beam and mass block structure. When the measured object vibrated, the central wavelength of the vibration sensing grating on the elastic steel plate changed. Through the data analysis system, the wavelength drift of the vibration sensing grating caused by temperature change and the wavelength drift of the vibration sensing grating caused by vibration change were distinguished and the vibration measurement could be realized according to the acceleration sensitivity obtained in the calibration experiment. The wavelength drift of the vibration sensing grating caused by the temperature change separated by the data analysis system could be used as the temperature compensation of the stress sensing grating and then the stress measurement could be realized according to the stress sensitivity obtained in the calibration experiment. However, the sensitivity was only 0.46 pm/g.

Figure 5 Schematic diagram of intensity detecting FBG-based acceleration sensor based on the matching filtering demodulation method

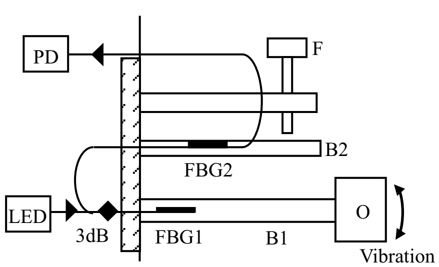
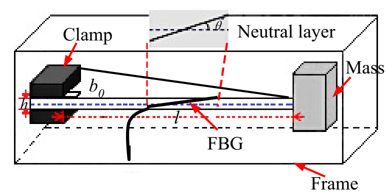


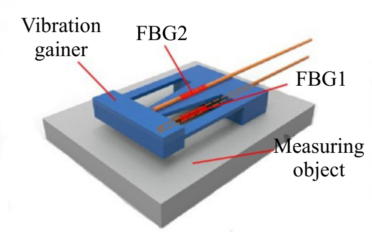
Figure 6 Schematic diagram of bandwidth detecting FBG-based acceleration sensor



In 2019, Yao *et al.* (2019) optimized the design of the elastic steel plate and encapsulated strain sensing and vibration sensing gratings on the surfaces of the measured object and cantilever beam of equal strength, respectively. According to the strain, temperature and acceleration sensitivity obtained in the calibration experiments, the same analysis system and measurement principles were used to realize the strain, temperature and vibration measurements and the sensitivity of the sensor was increased to 7.69 pm/g. Then, the optimized structure is shown in Figure 7.

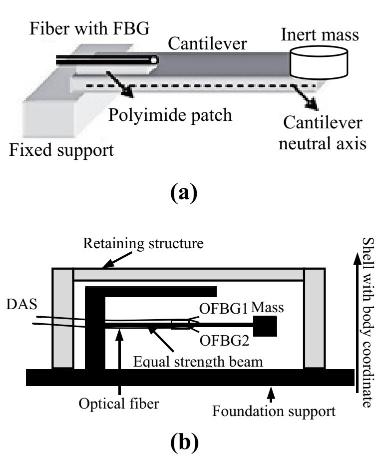
Due to the structural characteristics of cantilever beam and simply supported beam, acceleration sensors fail to solve the problem that resonant frequency and sensitivity restrict each other seriously. For this reason, Wang *et al.* (2011), Basumallick *et al.* (2011), Basumallick *et al.* (2013), Basumallick *et al.* (2016), Basumallick *et al.* (2020) and Guo *et al.* (2013a, 2013b, 2013c), Li *et al.* (2015a, 2015b, 2015c, 2015d) started with the vibration transfer efficiency to design a

Figure 7 Schematic diagram of FBG-based sensor for simultaneous measurement of strain, temperature and vibration



series of wavelength detecting FBG sensitized acceleration sensors. In 2011, Wang *et al.* (2011) fixed the cantilever beam on a special triangle bracket to improve the efficiency of external vibration transmission. In 2012, N. Basumallick pasted the polyimide (Basumallick *et al.*, 2011) or polytetrafluoroethylene (Basumallick *et al.*, 2013) patch on the surface of the cantilever beam and then pasted the FBG on the patch to increase the distance between the FBG and the neutral layer of the cantilever beam and designed two sensors whose sensitivities can be improved without affecting the resonant frequencies. Then the structure is shown in Figure 8(a). From 2013 to 2015, Guo *et al.* (2013a, 2013b, 2013c) and Li *et al.* (2015a, 2015b, 2015c, 2015d) designed two acceleration sensors with the same performance by adopting similar methods (Basumallick *et al.*, 2011; Basumallick *et al.*, 2013). In 2016, Basumallick *et al.* (2016) used the Teflon patch and special weighted processing method to design a sensitized acceleration sensor with widened working frequency band. In 2020, Basumallick *et al.* (2020) further optimized the previous structure and used a composite cantilever beam made of a polyurethane layer on a polyimide layer and a polymer fiber with a diameter of 80 μm to design two wide-band FBG accelerometers with different parameters for health monitoring

Figure 8 Schematic diagram of sensitized FBG-based acceleration sensor



Notes: (a) L beam - elastic diaphragm structure; (b) inverted cantilever beam structure

of electrical machines. Compared with common single-mode FBG, polymer FBG with higher sensitivity coefficient was implanted into the optimal position in the polyurethane layer away from the neutral layer of the cantilever beam, so that the sensor has better sensitivity while obtaining a wider working frequency band. The above sensors (Wang *et al.*, 2011; Basumallick *et al.*, 2011; Basumallick *et al.*, 2013; Basumallick *et al.*, 2016; Basumallick *et al.*, 2020; Guo *et al.*, 2013a, 2013b, 2013c; Li *et al.*, 2015a, 2015b, 2015c, 2015d) are suitable for vibration measurement occasion where the high sensitivity is required, but they did not solve the problem of the temperature-strain cross-sensitivity.

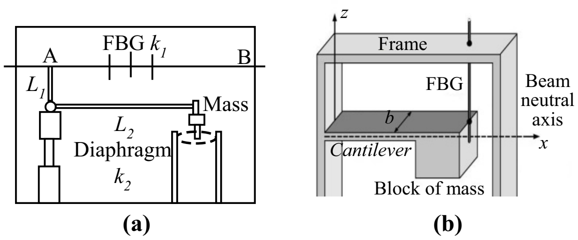
Different from the sensitization method mentioned above, Sun *et al.* (2008) and Gao *et al.* (2013) used intensity modulation and differential temperature-compensation method to symmetrically encapsulated two FBGs on the upper and lower surfaces of the cantilever beam and designed the temperature-compensation type acceleration sensors with high-sensitivity. However, Ye *et al.* (2012), Wang *et al.* (2013), Wang *et al.* (2013), Li and Liu (2014) and Khan *et al.* (2014) took the difference between the wavelength drifts of two FBGs varying with external vibration as the output signal of the sensor, which can double the sensitivity and achieve temperature compensation. In 2012, Ye and Wang *et al.* attached two FBGs to the upper and lower surfaces of the bow beam (Ye *et al.*, 2012) or the cantilever beam (Wang *et al.*, 2013) symmetrically, and the cantilever beam structure is shown in Figure 8(b). In 2013, Wang and Li *et al.* pasted two FBGs symmetrically on the upper and lower surfaces of double cantilever beams (Wang *et al.*, 2013) or double simply supported beams (Li and Liu, 2014). In 2014, Khan *et al.* (2014) attached two FBGs to the upper and lower surfaces of the curved cantilever beam symmetrically.

3.1.2 Two-point encapsulated fiber Bragg grating

Different from the previous section, many scholars designed a series of wavelength detecting FBG beam-type acceleration sensors based on the axial property of the fiber by using the two-point encapsulation method that can avoid the reflection chirp of the FBG. When the sensors were excited by the external vibration, axial inertial forces acting on the fibers caused FBGs to produce axial tension or compression.

From 2007 to 2009, Sun *et al.* (2007) and Costa Antunes *et al.* (2009) fixed one end of the FBG on the shell and the other end on the L-shaped beam by two-point encapsulation. As the FBG is directly used as the elastic element, the sensor has high sensitivity, but the grating is easy to be broken. In 2011, Weng *et al.* proposed the FBG accelerometer based on the L-shaped beam (Weng *et al.*, 2011) or the U-shaped beam (Weng *et al.*, 2012) connected with the diaphragm and the L-shaped beam structure is shown in Figure 9(a). The elastic diaphragm limits the non-working axial motion, which greatly reduces the transverse cross-sensitivity. In 2014, Zhang *et al.* (2014a, 2014b) added silicone oil damping to the sensor based on the L-shaped beam structure, which inhibited the resonance and widened the working frequency band of the sensor. In 2016, Xiang *et al.* (2016) designed a high-sensitivity acceleration sensor based on the principle that the strain increases linearly with the distance from the neutral layer of the cantilever beam. In 2017, Ramos and Romero (2017) changed the relative

Figure 9 Schematic diagram of two-point encapsulated FBG-based acceleration sensor

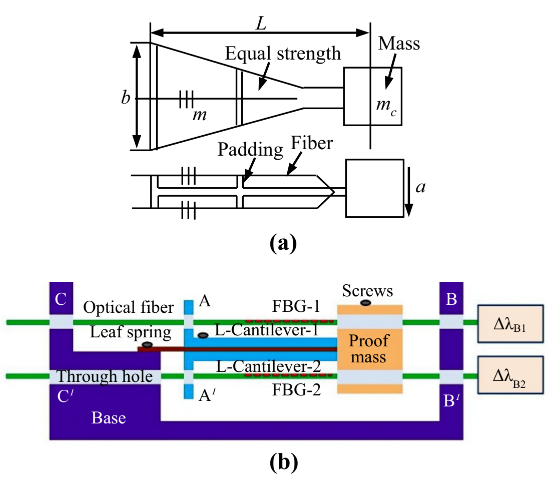


Notes: (a) Cantilever beam - patch structure; (b) cantilever beam - double FBGs structure

position of traditional beam structure and optical fiber and designed a sensor whose resonant frequency was improved without affecting the sensitivity. The structure is shown in Figure 9(b).

In contrast to the above structures based on the single FBG, Antunes *et al.* (2010) and Sun *et al.* (2009) symmetrically fixed two FBGs between the beam and the shell by two-point encapsulation in 2011. The synthetic drifts caused by the temperature and cross-axis vibration were eliminated by using the difference between the wavelength drifts of two FBGs. In 2014, Zhang *et al.* (2014a, 2014b) changed the traditional cantilever beam structure and fixed the FBG at the positions of two semi-circular holes of the cantilever beam, respectively, and designed a high-sensitivity acceleration sensor for low-frequency vibration measurement. In 2015, Wang *et al.* (Wang, 2015) suspended two FBGs between the pad and the housing and designed the sensitized FBG acceleration sensor based on the principle that the strain increases linearly with the distance from the neutral layer of the beam and the structure is shown in Figure 10(a). In 2019, Panda *et al.* (2019; Panda *et al.*, 2019) optimized the traditional L-shaped beam structure and designed

Figure 10 Schematic diagram of temperature self-compensating FBG-based accelerometer based on beam structure



Notes: (a) Cantilever beam - pad block structure; (b) double L-shaped beams structure

two kinds of temperature self-compensation acceleration sensors that are not sensitive to cross-axis vibration. Compared with the sensor based on the T-shaped beam structure (Panda *et al.*, 2019), the overall performance of the sensor based on the double L-shaped beams structure (Panda *et al.*, 2019) has been further improved. The structure is shown in Figure 10(b).

In summary, the basic information of the structures, parameters (resonant frequency, working frequency band and sensitivity) of the FBG acceleration sensors based on the beam structures is shown in Table 1.

3.2 Fiber Bragg grating acceleration sensor based on transverse property of the fiber

Generally, the frequency below 150 Hz belongs to low frequency, while the frequency within the range of 150-500Hz belongs to intermediate-low frequency. The sensors based on the cantilever beam structure are often used in low frequency or intermediate-low frequency fields because of the mutual restriction between the sensitivity and the resonant frequency. Some scholars use the principle that the slightly stretched FBG is more sensitive to transverse force than axial force and convert the vertical vibration of the inertial object in direct contact with the fiber into the axial stretch or compression of the FBG and design a series of low frequency or intermediate-low frequency FBG acceleration sensors. The FBG acceleration sensors are introduced below from the aspect of the measuring frequency in different ranges.

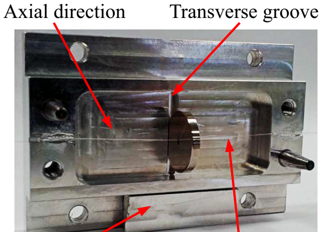
3.2.1 Fiber Bragg grating acceleration sensor with low frequency

In 2009, Talebinejad *et al.* (2009) attached the lumped mass guided through a precisely machined tube to the fiber and designed a wavelength detecting FBG acceleration sensor with good anti-interference ability. The FBG between the mass block and the shell was subjected to the transverse force more sensitive than the axial force and the sensitivity of the sensor was improved. From 2013 to 2015, Li *et al.* placed the mass block in which the cross-axis vibrations were limited in the middle of the fiber (Li *et al.*, 2013) or connected the fiber with the transverse rod (Li *et al.*, 2015a, 2015b, 2015c, 2015d) and made the FBG between the inertial object and the shell to design two-wavelength detecting FBG acceleration sensors with high sensitivity. Then one of these structures is shown in Figure 11(a). Instead of using common single-mode FBG (Talebinejad *et al.*, 2009; Li *et al.*, 2013; Li *et al.*, 2015a, 2015b, 2015c, 2015d), Ni *et al.* (2013) took the double-cone FBG as a sensing element and used an intensity detecting system to convert the wavelength drift into the light power variation and the value of the external acceleration could be measured by detecting the change of the light power in 2013 and the structure is shown in Figure 11(b). In the same year, Zhang *et al.* (2013) directly etched a small mass block on a fiber with an etched FBG and a not etched FBG to design an intensity detecting FBG micro-sensor for simultaneous measurement of vibration and temperature. Not etched FBG only sensitive to temperature was used to measure external temperature and etched FBG sensitive to both vibration and temperature was used to measure external vibration under not etched FBG compensation. However, the above sensors (Ni *et al.*, 2013; Zhang *et al.*, 2013) lost the advantage of wavelength coding and

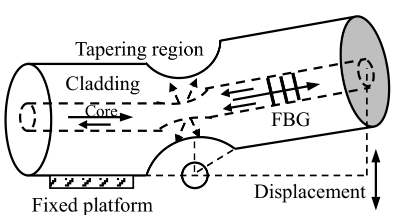
Table 1 Basic information of the FBG acceleration sensors based on the beam structures

Reference	Configuration	Resonant frequency (Hz)	Working frequency band (Hz)	Sensitivity (pm/g)	Encapsulation mode
Tiwari *et al.* (2019)	FBG is attached to the curved cantilever beam	/	5–100	88	Full encapsulation
Udos *et al.* (2020)	FBG is attached to cantilever beam combined with magnetic damper to suppress the resonance	/	20–100	/	Full encapsulation
Jiang *et al.* (2009)	Sensing FBG and matching FBG are, respectively, attached to the main beam and auxiliary beam	250	/	/	Full encapsulation
Li *et al.* (2009)	FBG is obliquely adhered in the outside of simply supported beam	/	/	0.4 nm/g	Full encapsulation
Yao *et al.* (2019)	FBGs are, respectively, pasted on the measured object and stainless steel plate	/	/	7.69	Full encapsulation
Wang *et al.* (2011)	FBG is pasted on a cantilever beam of equal strength attached to a special triangular bracket	100	0–75	285	Full encapsulation
Basumallick *et al.* (2013)	FBG is adhered in the polytetrafluoroethylene patch pasted on the surface of the cantilever beam	18.75	0–10	1,062	Full encapsulation
Wang *et al.* (2013)	FBGs are symmetrically attached to the upper and lower surfaces of two cantilever beams	80.74	0–50	208.5	Full encapsulation
Weng *et al.* (2011)	FBG is fixed between the L-shaped beam and the housing connected with the elastic diaphragm	220	0–110	106.5	Two-point encapsulation
Xiang *et al.* (2016)	FBG is suspended above the cantilever structure based on the principle of strain enlargement	125	/	750	Two-point encapsulation
Ramos and Romero (2017)	FBG is fixed between the frame and the inverted cantilever beam	227.3	10–210	339	Two-point encapsulation
Zhang *et al.* (2014a)	FBGs are, respectively, fixed at the positions of two semi-circular holes of the cantilever beam	60	0–25	1,296.47	Two-point encapsulation
Wang (2015)	FBGs are suspended above and below between the pad block and the housing	70	1–55	1,013.4	Two-point encapsulation
Panda *et al.* (2019)	FBGs are fixed between the double L-shaped beams and the base	86	5–50	406.7	Two-point encapsulation

Figure 11 Schematic diagram of radial vibration FBG-based accelerometer



(a)



(b)

Notes: (a) Common single-mode FBG; (b) double conical FBG

were easily affected by the fluctuation of the light source. In 2016, Li *et al.* (2016) improved the structure (Li *et al.*, 2013) and threaded an optical fiber with two FBGs through the mass block to make two FBGs symmetrical about the mass block and used baffles that limited the mass block to vibrate along the x and z directions to design a super-sensitive FBG acceleration sensor with strong anti-interference capability. When the mass block vibrated along the radial direction of the fiber, two FBGs generated the same strain owing to the same motion, while when the mass block was disturbed by the vibration of the cross-axis (x-axis), two FBGs generated opposite strain owing to opposite motion. Therefore, the sum between the wavelength drifts of two FBGs could be used as the output signal of the sensor to double the sensitivity and further reduce the interference of the cross-axis vibration.

3.2.2 Fiber Bragg grating acceleration sensor with intermediate-low frequency

The resonant frequencies of the sensors in the above section are not higher than 45 Hz, which can only be applied to some low-frequency areas, such as the reservoir and the seismic monitoring, and they cannot meet the measurement requirements in most fields. In 2017, Li *et al.* (2017a, 2017b, 2017c, 2017d) improved the structure (Li *et al.*, 2013) by setting two through holes on the mass block with respect to the z-axis symmetry and using baffles that limited the mass block to vibrate along the x and y directions. By parallel arranging a fiber with FBG and a metal beam with a good elastic coefficient through the mass block, FBG was positioned between the mass block and the shell, and a wavelength detecting FBG acceleration sensor with good impact resistance was designed for intermediate-low frequency vibration measurement. However, the sensor did not solve the problem of the temperature-strain cross-sensitivity. In the same year, Li *et al.* (2017a, 2017b, 2017c, 2017d) designed the temperature self-compensation and intermediate-low frequency acceleration sensor based on the double FBGs – diaphragm structure and the structure without external vibration excitation is shown in Figure 12. It can be seen from Figure 12 that the mass block – diaphragm structure made two fibers arranged symmetrically and parallel to the diaphragm produce the same amount of deformation. When the mass block vibrated along the radial direction of the fiber, two FBGs generated opposite strain owing to opposite motion. Therefore, the difference between the wavelength drifts of two FBGs could be used as the output signal of the sensor to double the sensitivity and realize temperature compensation.

To sum up, the basic information of the structures, parameters (resonant frequency, working frequency band and sensitivity) of the FBG acceleration sensors based on the transverse property of the fiber is shown in Table 2.

3.3 Fiber Bragg grating acceleration sensor based on elastomer structure

The resonant frequency of the FBG acceleration sensor based on the beam structure or the transverse property of the fiber is not high, which cannot meet the requirements of medium-high frequency vibration testing in electro-mechanical, aerospace and other fields. Therefore, some scholars have designed some acceleration sensors based on the elastomer structure. The function of the special elastomer is to increase the elastic coefficient of the system to improve the resonant frequency of the sensor. However, by using the elastomers of different materials and structures, different performance sensors were obtained. The FBG acceleration sensor based on the elastomer structure will be introduced in detail below.

3.3.1 Acceleration sensor based on elastic cylinder structure

Compared with the sensor based on traditional beam structure, many scholars have designed some wavelength detecting FBG acceleration sensors based on the elastic cylinder structure. In 2015, Zhang *et al.* (2015) and Wang *et al.* (2015b) implanted the fiber with the FBG into the axis position of the soft cylinder made of special materials, which can reduce the cross-sensitivity of the transverse axis and protect the FBG from damage. Compared with the single cylinder structure designed by Zhang *et al.* (2015), the symmetrical push-pull structure based on the double cylinder designed by Wang *et al.* (2015b) not only eliminate the synthetic drifts caused by temperature and cross-axis vibration by using the difference principle but also significantly improve the sensitivities of sensors. Then the symmetrical push-pull structure is shown in Figure 13. Compared with the sensor (Wang *et al.*, 2015b) designed by Wang *et al.*, in the same year, Wang *et al.* (2015a) used two-point encapsulation mode and embedded two FBGs into the

Figure 12 Schematic diagram of temperature self-compensating FBG-based accelerometer based on diaphragm structure

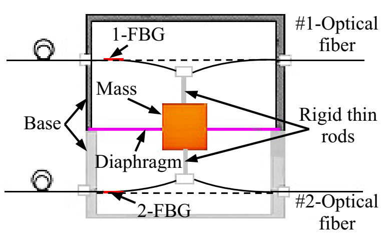


Figure 13 Schematic diagram of FBG-based acceleration sensor based on symmetrical push-pull structure

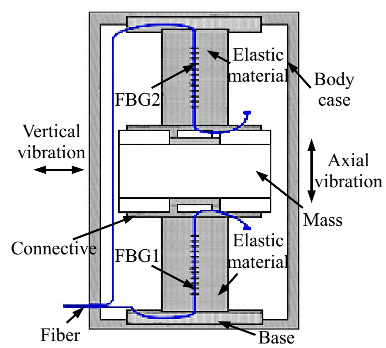


Table 2 Basic information of the FBG acceleration sensors based on transverse property of the fiber

Reference	Configuration	Resonant frequency (Hz)	Working frequency band (Hz)	Sensitivity (pm/g)	Encapsulation mode
Talebinejad *et al.* (2009)	Lumped mass guided through a precisely machined tube is attached to the fiber	50	/	200	Two-point encapsulation
Li *et al.* (2013)	Fiber section with the FBG has a mass block hanging in the middle	25	0–12	1,333	Two-point encapsulation
Li *et al.* (2015)	Fiber with FBG is connected to the transverse rod	43	/	1,240	Two-point encapsulation
Ni *et al.* (2013)	A double conical FBG free end is attached to a mass block	20	/	4.85 nw/g	Two-point encapsulation
Li *et al.* (2016)	Fiber section with two FBGs has a mass block hanging in the middle	34	0–22	2,362	Two-point encapsulation
Li *et al.* (2017a, 2017b, 2017c, 2017d)	Fiber with FBG and a metal beam are arranged in parallel through the mass block	400	12–250	193.6	Two-point encapsulation
Li *et al.* (2017a, 2017b, 2017c, 2017d)	Two fiber sections with FBG have a mass block connected with elastic diaphragm in the middle	300	10–150	31.25	Two-point encapsulation

double-cylinder with the changed radius and designed an FBG acceleration sensor with higher sensitivity and resonant frequency by using the difference principle. To balance the sensitivity and resonant frequency of the sensor to achieve the optimal overall performance, Liu *et al.* (2019) embedded the FBG into an elastic cylinder connected with the double-diaphragm by means of two-point encapsulation and designed an FBG acceleration sensor with high sensitivity in 2019, which has the potency for the important field of low-frequency oil-gas seismic exploration.

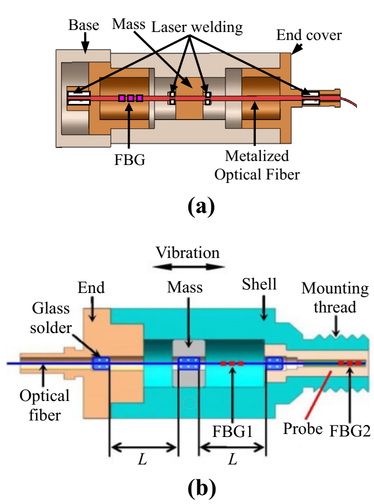
3.3.2 Acceleration sensor based on elastic optical fiber structure

From 2009 to 2012, Guo *et al.* (2009) and Liang *et al.* (2012) took the elastic optical fiber as the elastic element directly and used the two-point encapsulation method to suspend FBG between the mass block supported by the elastic clasps (Guo *et al.*, 2009) or spring (Liang *et al.*, 2012) and the shell, and, respectively, designed a wavelength detecting FBG acceleration sensor with high sensitivity. Compared with the ordinary single-mode optical fiber (Guo *et al.*, 2009), A. Stefani (Stefani *et al.*, 2012) and Guo *et al.* (2013a, 2013b, 2013c) used special optical fibers as the elastic elements, which improved the elastic coefficient of the system and extended the life cycle of the sensor. In 2012, the former (Stefani *et al.*, 2012) used the polymer fiber as the elastic element, while the latter (Guo *et al.*, 2013a, 2013b, 2013c) used the metalized fiber as the elastic element in 2013 and the structure is shown in Figure 14(a). They have both designed the wavelength detecting FBG acceleration sensors, but the cost of the sensors was very high and the problem of the temperature-strain cross-sensitivity was not solved. In 2017, Han *et al.* (2017) suspended two FBGs symmetrically between the mass block supported by elastic plate and the pedestal by means of two-point encapsulation and designed a wavelength detection and temperature self-compensation FBG acceleration sensor. In 2018, Kishore (2018) took the optical fiber based on the single mode-multimode-single mode structure as the elastic element and designed a temperature-insensitive seismic vibration sensor by adopting the intensity modulation method and special interrogation system. In 2018, Wang *et al.* (2018a, 2018b) improved the previous structure (Guo *et al.*, 2013a, 2013b, 2013c) and designed a wavelength detecting sensor for the vibration and temperature monitoring of train bearing by using two ordinary single-mode FBGs and the reference grating temperature-compensation method. The structure is shown in Figure 14(b). Relative to the sensor with low acceleration sensitivity (Wang *et al.*, 2018a, 2018b), in 2020, Guo *et al.* (2020) supported the mass block with the three-dimensional-printed hexagonal configurations that can work normally below 200°C and fixed both ends of the fiber part with the vibration sensing grating in the pinholes of two elbows by means of two-point encapsulation and make the fiber part with temperature sensing grating hang freely to design a wavelength detection and high sensitivity FBG acceleration sensor based on the reference grating temperature-compensation method.

In the same year, Kuhn *et al.* (2020) and Xu *et al.* (2020), respectively, designed a wavelength detecting FBG sensor for multi-parameter measurement. The former (Kuhn *et al.*, 2020) designed a spring-shaped structure made of the carbon fiber reinforced composite with the quick-coupling clip function. Both ends of the fiber part with the vibration sensing grating were fixed in grooves on both sides by means of two-point encapsulation and the fiber part with temperature sensing grating was suspended freely inside the metal tube glued to the groove to realize the simultaneous measurement of temperature and vibration. Then the structure is shown in Figure 15(a). The latter (Xu *et al.*, 2020) symmetrically suspended two FBGs between studs by means of two-point encapsulation and separated the difference signals of two FBG wavelength drifts caused by external tilt and vibration excitations by means of the wavelet transform method to design a pendulum-type FBG sensor for simultaneous measurement of tilt and acceleration and the structure is shown in Figure 15(b).

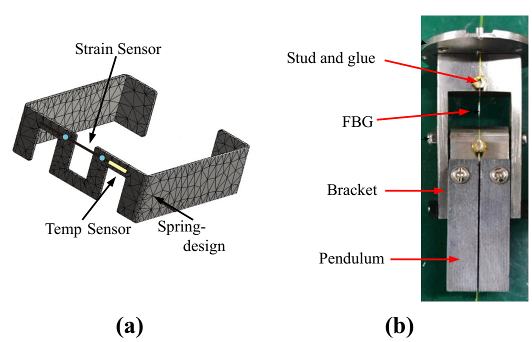
To meet the performance requirements of acceleration sensors in different fields, some scholars made the sensor cores into integrated structures with hinges of different

Figure 14 Schematic diagram of FBG-based acceleration sensor based on elastic optical fiber structure



Notes: (a) metal - coated FBG; (b) double common single-mode FBG

Figure 15 Schematic diagram of FBG-based sensor for multi-parameter measurement



Notes: (a) Temperature and vibration; (b) tilt and acceleration structures and sizes and designed some wavelength detecting acceleration sensors with intermediate-high frequency or high sensitivity. From 2016 to 2017, Liang *et al.* used the optical fiber as the elastic element and proposed the intermediate-high frequency FBG accelerometers based on the single-hinge structure (Liang *et al.*, 2016) and the multi-hinge structure (Qiu *et al.*, 2017) and the multi-hinge structure is shown in Figure 16(a). From 2015 to 2017, Dong *et al.* fixed the FBG by two-point encapsulation in the middle of the symmetric hinge and designed an intermediate-high frequency acceleration sensor (Dai *et al.*, 2015) and a high-sensitive acceleration sensor (Dong *et al.*, 2017). The structure is shown in Figure 16(b). When the mass block vibrates under external excitation, both ends of the grating will produce axial strain in the opposite direction due to the hinge rotation, thus doubling the sensitivity of the sensor. In 2019, Li *et al.* (2019) combined hinges and rectangular plates to design a miniaturized sensor for vibration monitoring of rotating machinery, which could achieve the distributed measurement. In 2019, Yan and Liang (2020) improved the previous structures (Liang *et al.*, 2016; Qiu *et al.*, 2017) and designed a high-sensitivity acceleration sensor based on the parallel double flexible hinges structure, which is insensitive to cross-axis vibration and has strong impact resistance. Compared with the sensors based on flexible hinge structures, in 2019, Xie *et al.* (2020) designed a super-high sensitivity sensor for low-frequency vibration measurement by adopting a rigid-hinge symmetric structure that makes the fiber generate greater deformation and higher sensitivity and the structure is shown in Figure 16(c).

3.3.3 Acceleration sensor based on elastic diaphragm structure

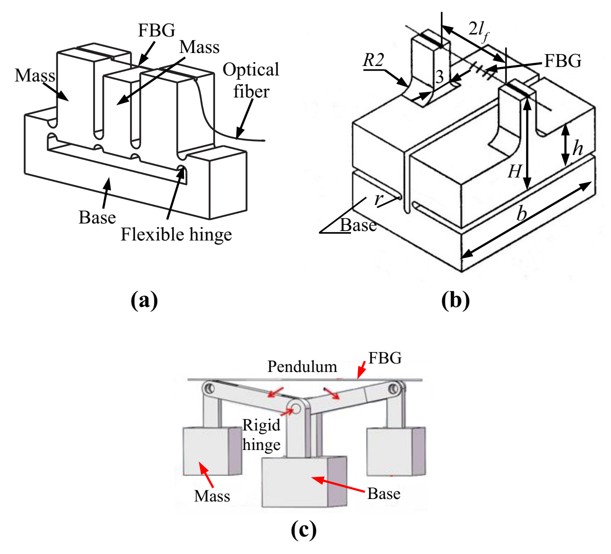
Compared with the acceleration sensor based on the ordinary elastic fiber-mass block structure, wavelength detecting FBG acceleration sensor based on the elastic diaphragm-mass block structure can obtain higher resonant frequency. Muller *et al.* (2009) and Liu *et al.* (2014) used the double-diaphragm structure with the high elastic coefficient to limit the vibration of the mass block in the non-working axial and designed the accelerometers suitable for the field of the intermediate-high frequency vibration measurement. In contrast to the structures based on the double-diaphragm and single-FBG, Yin *et al.* (2014) adopted the structure based on the single-diaphragm and double-FBG to eliminate the synthetic shift caused by temperature with the difference method in 2014, which significantly improved the sensitivity of the sensor. Then the structure is shown in Figure 17(a). In 2017, Li *et al.* (2017a, 2017b, 2017c, 2017d) improved the structure designed by Yin *et al.* (2014) and used the reference grating temperature-compensation method to realize the measurement of the acceleration and temperature.

Compared with the sensors based on the mass block structures to conduct vibration, Li *et al.* (2013, 2014, 2015a, 2015b, 2015c, 2015d) designed a series of non-contact sensors for vibration monitoring of rotating machine based on the single FBG-elastic diaphragm structures from 2013 to 2015. When the rotating shaft vibrates, the gap between the permanent magnet of the sensor mounted on the rotating shaft and the rotating shaft changes and the magnetic force of the elastic diaphragm changes, thus changing the axial strain of the FBG, and finally realizing the vibration detection of the rotating machine by detecting the wavelength drift of the FBG. Compared with the above sensors (Li *et al.*, 2013, 2014, 2015a, 2015b, 2015c, 2015d) that did not realize temperature compensation, Tan *et al.* (Li *et al.*, 2016) encapsulated double FBGs in accordance with the corresponding rule in 2016 and adopted the reference grating temperature-compensation method to achieve high-precision measurement for the vibration of the rotating shaft in the environment of variable temperature and the structure is shown in Figure 17(b).

3.3.4 Acceleration sensor based on elastic tube structure

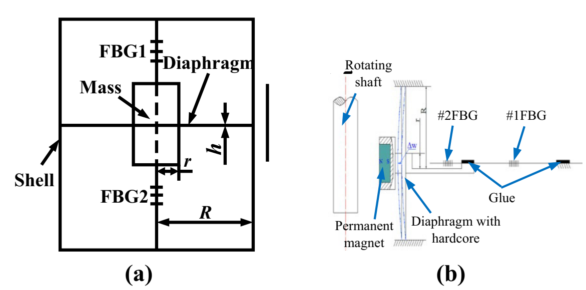
To avoid direct tension or compression of the optical fiber, Wang *et al.* (2009) and Zhang *et al.* (2011a, 2011b) designed the wavelength detecting FBG acceleration sensors with significantly higher resonant frequency and sensitivity by using metal bellows with different elastic coefficients, but two sensors did not have temperature compensation. In

Figure 16 Schematic diagram of FBG-based acceleration sensor based on hinge structure



Notes: (a) Multi-hinge structure; (b) symmetrical hinges structure; (c) rigid hinge structure

Figure 17 Schematic diagram of FBG-based accelerometer based on diaphragm structure



Notes: (a) Diaphragm - mass structure; (b) diaphragm - permanent magnet structure

2018, Wang *et al.* (2018a, 2018b) embedded the fiber with two FBGs into the capillary steel tube and used the difference principle to design a temperature self-compensation FBG acceleration sensor based on the wavelength modulation principle. Then the structure is shown in Figure 18.

3.3.5 Acceleration sensor based on elastic shell structure

To give full play to the advantages of the small size and lightweight of FBG acceleration sensor, Wang *et al.* (2016) and Gutiérrez *et al.* (2018) started from the material and internal structure of the sensor and designed the miniaturized FBG accelerometers based on the wavelength modulation principle. In 2016, the former (Wang *et al.*, 2016) placed the mass block inside the thin polyurethane shell and the sensor had great advantages in forming a small three-dimensional FBG accelerometer and a very large vector sensor array. In 2018, the latter (Gutiérrez *et al.*, 2018) used the hexagonal lattice hollow shell as an elastomer and the sensor could be installed inside many small devices for structural health monitoring. The structure is shown in Figure 19(a). However, they did not solve the problem of temperature-strain cross-sensitivity. In 2017, Zhu *et al.* (2017) improved the previous structure (Wang *et al.*, 2016) and adopted a double FBGs-symmetric push-pull structure to realize temperature compensation. The structure is shown in Figure 19(b).

To sum up, the basic information of the structures, parameters (resonant frequency, working frequency band and sensitivity) of the acceleration sensors based on the elastomer structures is shown in Table 3.

Figure 18 Schematic diagram of FBG-based accelerometer based on capillary steel tube structure

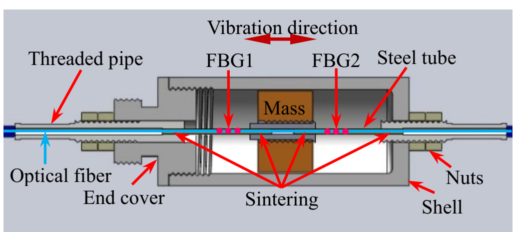
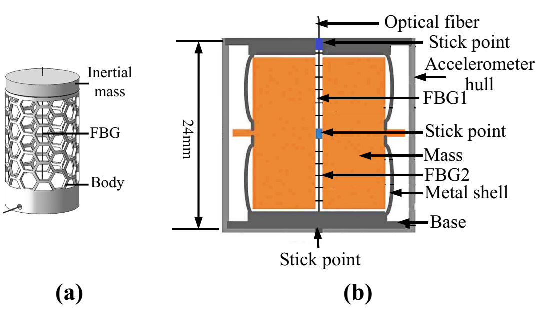


Figure 19 Schematic diagram of FBG-based acceleration sensor based on miniaturized structure



Notes: (a) Hexagonal lattice hollow shell structure; (b) symmetrical push-pull structure

4. Fiber Bragg grating based multi-dimensional acceleration sensor

Due to the complexity and multi-dimensionality of vibration, the common FBG based one-dimensional acceleration sensor cannot meet the requirements of aerospace, robotics and other multi-dimensional measurement fields. Therefore, the research on FBG based two-dimensional and three-dimensional acceleration sensors is increasing gradually. According to the principle of information detection and monitoring architecture, the extensive application of FBG-based multi-dimensional acceleration sensor in vibration monitoring is summarized and classified, as shown in Figure 20.

4.1 Fiber Bragg grating based two-dimensional acceleration sensor

As the difficulty of two-dimensional measurement is much greater than that of one-dimensional measurement, the number of FBG in the sensor is more than that of one-dimensional measurement and the structure is more complex than that of one-dimensional measurement. Scholars often, respectively, detect the acceleration in two dimensions and then conduct vector synthesis for the acceleration to obtain the acceleration in the two-dimensional plane. Wavelength detecting FBG two-dimensional acceleration sensor will be introduced from the aspect of the different vibration modes.

4.1.1 Axial-vibration type acceleration sensor

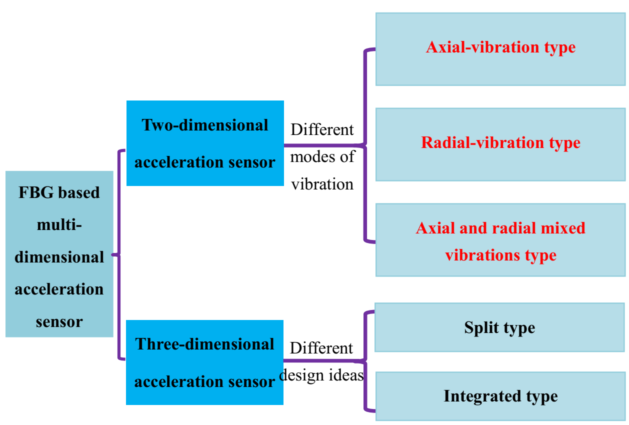
By means of two-point encapsulation, a certain number of FBGs were suspended in the specific positions and a series of axial-vibration type FBG two-dimensional acceleration sensors based on axial and transverse properties of the fiber were designed. Under the excitation of the external vibration along the axial-directions of the specific fibers, the specific FBGs were stretched or compressed due to the axial properties of the specific fibers, while other FBGs were stretched or compressed due to the transverse properties of the fibers.

Paulo *et al.* suspended four FBGs pairwise and fixed them between the mass block and the matrix and designed two temperature self-compensation FBG two-dimensional acceleration sensors. Compared with the first sensor using the ordinary single-mode fiber (Antunes *et al.*, 2012; Costa Antunes *et al.*, 2012; Linessio *et al.*, 2016), the second sensor using the ultra-high numerical aperture fiber (Linessio *et al.*, 2019) has higher resonance frequency and smaller size and can be installed inside a variety of small equipment for structural health monitoring. Then the structure is shown in Figure 21(a). Under the excitation of the external vibration along the axial-directions of the fibers where FBG1 and FBG3 were located, FBG1 and FBG3 produced opposite strain changes due to the opposite motion, while FBG2 and FBG4 produced the same strain changes due to the same motion. Similarly, the vibration excitation in another direction caused the opposite effect. Therefore, the vibrations in different directions could be sensed by the difference between the wavelength drifts of the grating pairs, which eliminated the same wavelength drifts caused by temperature change and cross-axis vibration to realize the two-dimensional acceleration measurement. In 2017, Wang *et al.* (2017) adopted a quality-ring position adjustable structure and designed a sensitivity adjustable two-dimensional acceleration sensor and the structure is shown in Figure 21(b).

Table 3 Basic information of the acceleration sensors based on the elastomer structures

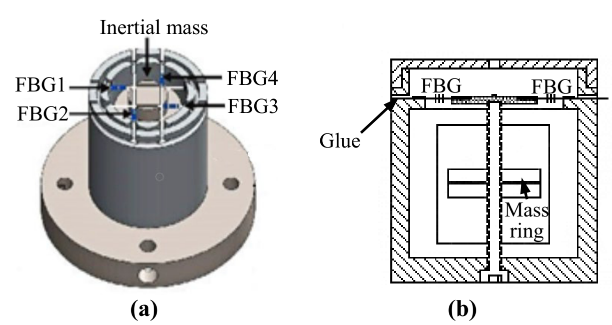
Reference	Configuration	Resonant frequency (Hz)	Working frequency band (Hz)	Sensitivity (pm/g)	Encapsulation mode
Wang *et al.* (2015a, 2015b)	FBGs are symmetrically embedded in two radial varying elastic cylinders	449	0–300	623	Two-point encapsulation
Liu *et al.* (2019)	FBG is embedded in the elastic cylinder connected with double elastic diaphragms	441	5–300	152	Two-point encapsulation
Liang *et al.* (2012)	FBG is suspend between the mass block supported by the spring and the shell	28	/	2,131.5	Two-point encapsulation
Stefani *et al.* (2012)	Polymer fiber FBG is fixed between two ends of the forked structure	2,900	10–1,000	19	Two-point encapsulation
Guo *et al.* (2013)	Metallized fiber FBG is fixed between the mass and the base	3,600	50–1,000	1.7	Two-point encapsulation
Han *et al.* (2017)	FBGs are symmetrically suspended between the mass block supported by elastic plate and the pedestal	280	20–200	900	Two-point encapsulation
Guo *et al.* (2020)	Vibration sensing grating is suspended between two elbows and temperature sensing grating hangs freely	124.9	10–110	421.4	Two-point encapsulation
Xu *et al.* (2020)	FBGs are symmetrically suspended between studs	32	0–20	2,430	Two-point encapsulation
Qiu *et al.* (2017)	FBG is fixed between the mass blocks connected by four flexible hinges	2,300	50–800	29	Two-point encapsulation
Xie *et al.* (2020)	FBG is fixed between the pendulums connected by the rigid hinge	39	0–30	949.2	Two-point encapsulation
Liu *et al.* (2014)	FBG is fixed between the matrix and the mass block fixed by two elastic membranes	1,240	50–800	45.9	Two-point encapsulation
Yin *et al.* (2014)	FBGs are symmetrically fixed between the housing and the mass block fixed by the elastic diaphragm	204	10–150	53.56	Two-point encapsulation
Li *et al.* (2014)	FBG is fixed between the diaphragm and the base	1,500	0–1,300	/	Two-point encapsulation
Wang *et al.* (2009)	Fiber with FBG is embedded in a metal bellow	242.9	0–100	162.8	Two-point encapsulation
Wang *et al.* (2018a, 2018b)	FBGs about mass block symmetry are embedded into the capillary steel tube	3,806	0–1,200	4.01	Two-point encapsulation
Gutiérrez *et al.* (2018)	FBG is fixed between the mass and the base	708	0–236	19.65	Two-point encapsulation
Zhu *et al.* (2017)	FBGs are, respectively, fixed between the mass and the base	1,175	30–300	9.4	Two-point encapsulation

Figure 20 Schematic classification diagram of FBG-based multi-dimensional acceleration sensor



They suspended four FBGs pairwise and fixed them between the fixed plate and the matrix and two-dimensional acceleration measurement was realized by the difference principle. The sensitivity can be adjusted so that it can be used in many work situations, which has a good application prospect.

Figure 21 Schematic diagram of axial-vibration type FBG-based two-dimensional acceleration sensor



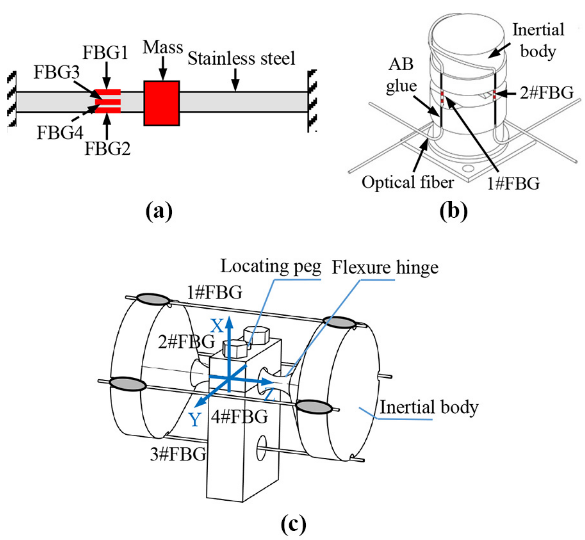
Notes: (a) Intermediate-high frequency; (b) low frequency

4.1.2 Radial-vibration type acceleration sensor

A certain number of FBGs were encapsulated in the specific positions of the elastomer by means of complete encapsulation or a certain number of FBGs were suspended in the specific positions by means of two-point encapsulation and a series of radial-vibration type FBG two-dimensional acceleration sensors were designed. Under the excitation of the external vibration along the radial-directions of the specific fibers, the specific FBGs of the sensor based on full-encapsulation mode were stretched or compressed and the wavelength drifts of the other FBGs were almost 0; FBGs of the sensor based on two-point encapsulation mode were stretched or compressed due to the axial property of the fiber.

In 2012, Guo *et al.* (2012) pasted four FBGs on the surface of the steel tube according to the corresponding rules and the structure is shown in Figure 22(a). Under the excitation of the external vibration along the radial-directions of the fibers where FBG1 and FBG2 were located, FBG1 and FBG2 produced opposite strain changes, while the strain of FBG3 and FBG4 was basically 0. Similarly, the vibration excitation in another direction caused the opposite effect. The two-dimensional measurement and temperature compensation are realized by using the difference principle, but the sensitivity of the sensor is low. In 2013, P. Munendhar *et al.* (Munendhar and Khijwania, 2013) fixed the mass block between two special simply supported beams designed to achieve the uniform strain at the FBG pasted zone and encapsulated two FBGs on the upper and lower surfaces of two simply supported beams to design a one-dimensional acceleration detecting unit and two-dimensional acceleration measurement was realized by the combination of two one-dimensional sensing units in different directions. Compared with the structures (Guo *et al.*, 2012; Munendhar and Khijwania, 2013) with mutual restriction of resonant frequency and sensitivity, from 2017 to 2020, Zhang *et al.* (2017a, 2017b) and Song *et al.* (2020) replaced the elastic tube with a hinge and adopted the two-point encapsulation method to hang each FBG measuring uniaxial acceleration between the inertial object and the fixed end and designed the FBG two-dimensional acceleration sensors. Compared with the traditional hinge structure (Zhang *et al.*, 2017a, 2017b), the miniaturized acceleration sensor based on the orthogonal flexible hinge structure designed by the latter

Figure 22 Schematic diagram of radial-vibration type FBG-based two-dimensional acceleration sensor



Notes: (a) Elastic tube structure; (b) orthogonal flexible hinge structure; (c) symmetrical hinges structure

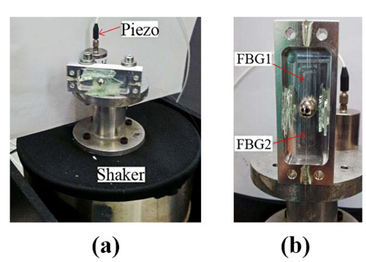
(Song *et al.*, 2020) in 2020 had higher resonant frequency and sensitivity and used a special hinge structure to reduce the transverse interference caused by an FBG measuring uniaxial acceleration, as shown in Figure 22(b). However, they did not solve the problem of temperature-strain cross-sensitivity. In 2019, Li *et al.* (2019) improved the structure (Zhang *et al.*, 2017a, 2017b) by adding, respectively, an FBG in the X and Y directions to form the four FBGs – symmetric hinge structure. Therefore, the difference between the wavelength drifts of the grating pairs was used as the output signal of the sensor to eliminate the same wavelength drifts caused by the temperature change and the cross-axis vibration and the two-dimensional acceleration measurement was realized. The structure is shown in Figure 22(c).

4.1.3 Axial and radial mixed vibrations type acceleration sensor

As the above two types of sensors measure the same vibration form in both dimensions, the resonant frequencies and sensitivities of their X-axis and Y-axis are roughly equal. In 2014, Li *et al.* (2014) designed an axial and radial mixed vibrations type FBG two-dimensional acceleration sensor based on axial and transverse properties of the fiber and the structure is shown in Figure 23. Under the excitation of the external vibration along the axial direction of the fiber, FBG1 and FBG2 produced opposite strain changes due to the opposite motion. Under the excitation of the external vibration along the radial-direction of the fiber, FBG1 and FBG2 produced the same strain changes due to the same motion. Therefore, the difference or sum of the two FBGs wavelength drifts was used as the output signal of the sensor to measure the axial or radial acceleration, which realized the two-dimensional vibration decoupling and measurement. In addition, owing to the measurement of uniaxial acceleration through different fiber property, the resonant frequencies and sensitivities of the sensor in the two dimensions are quite different.

From 2015 to 2017, Li *et al.* (2015a, 2015b, 2015c, 2015d; Li *et al.*, 2017a, 2017b, 2017c, 2017d) used similar principle (Li *et al.*, 2014) to design two kinds of FBG two-dimensional acceleration sensors. Relative to the single-hole mass block – double FBGs structure (Li *et al.*, 2015a, 2015b, 2015c, 2015d), Li *et al.* (2017a, 2017b, 2017c, 2017d) improved the structure of the mass block between the optical fiber in 2017. They passed through the fiber with two FBGs at the through-hole A of the mass block and the metal stiffening beam at through-hole B and C, respectively, to enhance the impact

Figure 23 Schematic diagram of axial and radial mixed vibrations type FBG-based two-dimensional acceleration sensor



Notes: (a) Radial vibration excitation; (b) axial vibration excitation resistance ability and anti-interference ability of coupling rotation of the sensor. The structure is shown in Figure 24.

In summary, the basic information of the structures, parameters (resonant frequency, working frequency band and sensitivity) of the FBG based two-dimensional acceleration sensors is shown in Table 4.

4.2 Fiber Bragg grating based three-dimensional acceleration sensor

Structures of three-dimensional acceleration sensors are more complex and the number of FBG used is more. Scholars generally design sensors from two perspectives: one is to arrange three FBG-based one-dimensional acceleration elements in the x, y and z axes of a sensor, and then conduct vector synthesis of the self-measured axial acceleration of the three sensing units to obtain the acceleration information in the three-dimensional space; The other is based on the structural principle of the single-component FBG acceleration sensor, which uses a mass block for three-component expansion and then combines the three axial accelerations measured at the same point to obtain the spatial acceleration information (Hou *et al.*, 2012). The following sensors will be introduced from two aspects.

4.2.1 Three-component split type acceleration sensor

Jiang *et al.* (2008) and Wang *et al.* (2012) designed the three-component split type wavelength detecting FBG acceleration sensors by using completely encapsulation. Compared with the cantilever beam structure adopted by the former in 2008 (Jiang *et al.*, 2008), the latter adopted an elastic steel cylinder with a high elastic coefficient in 2012 (Wang *et al.*, 2012) and the sensor has a high resonance frequency. Jiang (Jiang *et al.*, 2014) and Nan (Nan and Song, 2014; Nan and Li, 2016) *et al.* suspended and fixed each pair of FBGs between the L-shaped beams (Jiang *et al.*, 2014) or the mass blocks (Nan and Song, 2014; Nan and Li, 2016) and the matrix by using the two-point encapsulation. In 2013, the former (Jiang *et al.*, 2014) used the difference of wavelength drifts of each pair of FBGs as the output signal of the sensor to realize temperature compensation and three-dimensional measurement. From 2014 to 2016, the latter (Nan and Song, 2014; Nan and Li, 2016) adopted the method of intensity modulation to realize three-dimensional measurement. Although the sensor system had a lower cost, it lost the advantages of wavelength coding and was susceptible to the fluctuation of the light source. In 2015, Li *et al.* (2015a, 2015b, 2015c, 2015d) used the principle of wavelength modulation and combined a one-dimensional sensing unit and a two-dimensional sensing unit to realize three-dimensional measurement. The sensor not only reduced the number of sensing units to ensure the synchronization of acceleration in each of the dimensions but also realized the three-dimensional vibration decoupling and the structure is shown in Figure 25.

4.2.2 Three-component and one-body acceleration sensor

Compared with a three-component split type sensor combined with three same sensor units, the three-component and one-body sensor has the advantages of easy assembly, good stability and wide application range. Abushagur *et al.* (2005), Morikawa *et al.* (2002) and Masek *et al.* (2011), respectively, designed an integrated FBG acceleration sensor by using the central suspension structure based on the six FBGs and mass block. Under the excitation of the axial vibration along with the fiber, the corresponding grating pair based on the axial property of the fiber produced opposite wavelength drifts, while the other grating pairs based on the transverse property of the fiber produced the same wavelength drifts. The former (Abushagur *et al.*, 2005) adopted the principle of wavelength modulation to realize three-dimensional acceleration measurement, while the latter (Morikawa *et al.*, 2002; Masek *et al.*, 2011), respectively, designed an intensity detecting FBG acceleration sensor susceptible to the fluctuation of the light source. Relative to the sensors that used the fiber directly as the

Figure 24 Schematic diagram of string-type FBG-based two-dimensional acceleration sensor

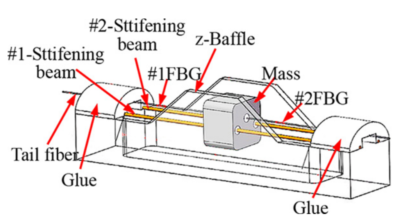
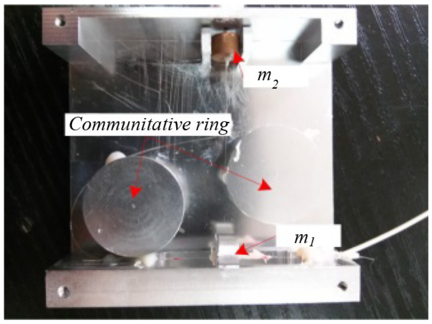


Table 4 Basic information of the FBG-based two-dimensional acceleration sensors

Reference	Configuration	Resonant frequency (Hz)	Working frequency band (Hz)	Sensitivity (pm/g)	Encapsulation mode
Linessio *et al.* (2019)	Four FBGs are fixed between the mass block and the matrix	X 1,232.5 Y 1,272.5	/	90	Two-point encapsulation
Guo *et al.* (2012)	Four FBGs are fixed on surface of steel tube	515	0–300	8.8	Full encapsulation
Song *et al.* (2020)	Two FBGs are fixed between the inertial body and the base	X 1,275 Y 1,482	20–800	X 41.2 Y 34.5	Two-point encapsulation
Li *et al.* (2019)	Four FBGs are fixed between the symmetrical hinges. According to different sizes, they are divided into max-sensor and min-sensor	Max 279.2 Min 814.3	Max 5–170 Min 20–600	Max 220 Min 40	Two-point encapsulation
Li *et al.* (2014)	Mass block is fixed between the optical fiber with two FBGs symmetry about the mass block	Radial 34.42 Axial 900	/	Radial 545 Axial 45.4	Two-point encapsulation
Li *et al.* (2017a)	Mass block has three through holes. A passes through the fiber with two FBGs, and B and C pass through a beam, respectively	Radial 225 Axial 1,074	Radial 10–150 Axial 10–800	Radial 52.7 Axial 21.5	Two-point encapsulation

Figure 25 Schematic diagram of FBG-based three-dimensional split acceleration sensor



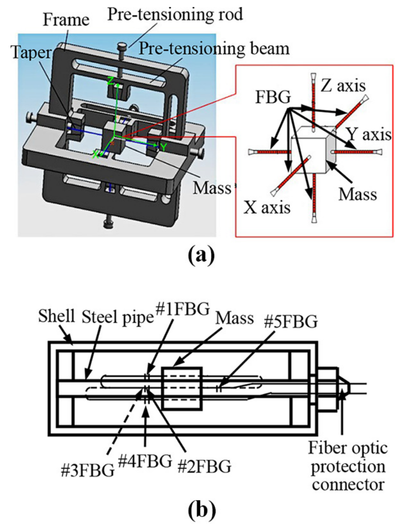
elastic deformation element (Abushagur *et al.*, 2005; Morikawa *et al.*, 2002; Masek *et al.*, 2011), Jiang and Yang (2012), Jiang and Yang (2013), used three scaffolds to support the mass block and embedded three optical fibers with two FBGs in scaffolds, respectively, to design intensity detecting FBG acceleration sensors with higher impact resistance and resonant frequency and the structure is shown in Figure 26(a). In contrast to the structure based on the six FBGs, Zhang *et al.* (Zhang *et al.*, 2012) improved the structure based on the four FBGs – stainless steel (Guo *et al.*, 2012) and pasted five FBGs on the surface of the steel tube in 2012, and the difference between the wavelength drifts of the grating pairs was used as the output signal of the sensor to realize three-dimensional measurement and temperature compensation and the structure is shown in Figure 26(b).

In summary, the basic information of the structures, advantages and disadvantages of the FBG-based three-dimensional acceleration sensors is shown in Table 5.

5. Commercial sensors

Most of the above sensors introduced only carry out amplitude-frequency characteristic testing and sensitivity calibration

Figure 26 Schematic diagram of FBG-based three-dimensional acceleration sensor



Notes: (a) Support frame structure; (b) elastic steel tube structure

experiments in the laboratory, which is mainly to verify the theoretical research and structural rationality of the sensor and a transition from theorization to commercialization. However, the performance of the commercial sensor has been strictly verified, which can easily and efficiently measure the vibration of the measured object. Moreover, most commercial sensors are uniaxial, which can realize multi-dimensional measurement through multi-axial integrated packaging or multi-directional layout installation according to customer requirements.

In recent decades, with the continuous development of fiber sensing technology, many companies producing commercial sensors have emerged across the world. The medium-low frequency sensors produced by MOI and Fiber Sensing have been used in the health monitoring of complex structures such as

Table 5 Basic information of the FBG-based three-dimensional acceleration sensors

Reference	Configuration	Merits and demerits	Encapsulation mode
Jiang *et al.* (2008)	Three FBGs are, respectively, fixed on three mutually perpendicular cantilevers of equal strength	Low cost and mature technology; resonant frequency and sensitivity restrict each other seriously	Full encapsulation
Wang *et al.* (2012)	Three FBGs are, respectively, fixed on the surfaces of three elastic steel cylinders	The resonant frequency is increased; no temperature compensation	Full encapsulation
Nan and Li (2016)	Three pairs of FBGs are, respectively, fixed between three mass blocks and the matrix	Temperature compensation is realized; the matching state of each pair of FBG is susceptible	Two-point encapsulation
Li *et al.* (2015)	The fiber section with two FBGs has a mass block hanging in the middle and another fiber has also a mass block hanging in the middle	Vibration decoupling is realized; FBGs are easy to broken	Two-point encapsulation
Abushagur *et al.* (2005)	A mass block is suspended and fixed to the geometric center of the shell by six orthogonal FBGs	Temperature compensation is realized; the resonant frequency is low and the band is narrow	Two-point encapsulation
Jiang and Yang (2013)	Three optical fibers with two FBGs are embedded into three supports supporting the mass block	Higher resonant frequency; it is susceptible to the fluctuation of light source	Two-point encapsulation
Zhang *et al.* (2012)	Five FBGs are fixed on the surface of the steel tube with mass block according to certain rules	Higher resonant frequency; FBG is prone to chirp	Full encapsulation

bridges, dams and buildings. Both sensors can be fixed to the surface of the measured object by adhesive and bolt, and multi-dimension measurement can be achieved through multi-axis integrated packaging. The "os7100" sensor produced by MOI (www.micronoptics.com) is shock-resistant and has a large range of 100 g, but has low sensitivity and resonant frequency. The "FS6500" sensor produced by Fiber Sensing (www.fibersensing.com) has a small range, but is highly reusable and sensitive, enabling multiple sensors to string together for distributed measurements of several kilometers. The pictorial diagrams of the two sensors are shown in Figure 27(a) and 27(b), respectively.

To meet the market demand for high-frequency vibration measurement, Gavea Sensors produces the high-frequency vibration sensor of "SmartAccel-40g"(www.monchina.com). The sensor has a large range, high resonant frequency and good reusing ability and can measure the vibration of the rotating structure. The pictorial diagram is shown in Figure 28(a). Different from the above three sensors, B&K has designed a vibration sensor of "4590" with a greater resonant frequency and range, higher sensitivity than the "SmartAccel-40g" after using a microstructural polymer fiber grating with higher strain sensitivity and strength than ordinary silicon dioxide fiber grating. Then the pictorial diagram is shown in Figure 28(b).

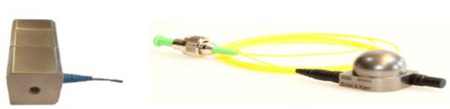
In addition, there are also many high-performance commercial sensors produced by Chinese companies. The "GS-TM-ZD-II" sensor produced by JSKJ (www.cgq.com) has a high sensitivity of 120 pm/g, but the resonant frequency is very low, only suitable for low-frequency vibration measurement. The "KNPAC-1" sensor (www.opxincai.com) produced by OPMATERIAL using differential temperature compensation method has a high sensitivity of 500 pm/g, but it is only suitable for low-frequency vibration measurement. The pictorial diagrams of the two sensors are shown in Figure 29(a) and 29(b), respectively.

Figure 27 Pictorial diagram of the commercial sensor with the medium-low frequency

(a) (b)

Notes: (a) "os7100" produced by MOI; (b) "FS6500" produced by fiber sensing

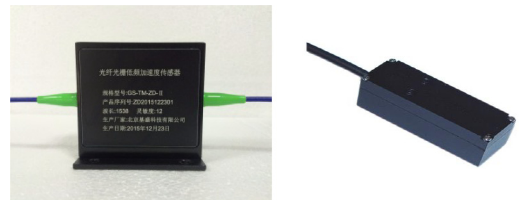
Figure 28 Pictorial diagram of the commercial sensor with the high frequency



(a) (b)

Notes: (a) "SmartAccel-40g" produced by Gavea Sensors; (b) "4590" produced by B&K

Figure 29 Pictorial diagram of the commercial sensor with the low frequency



(a) (b)

Notes: (a) "GS-TM-ZD-II" produced by JSKJ; (b) "KNPAC-1" produced by OPMATERIAL

According to the different requirements of the market for high-frequency vibration sensors, TECHNICA has produced two kinds of high-frequency vibration sensors of "T320" universal type and "T310" shock-resistant type (www.technicasa.com). The universal sensor has a high resonant frequency of 1,748 Hz and high sensitivity of 79.46 pm/g, but a small range. By contrast, the shock-resistant sensor has a very large range of 500 g and a very high resonant frequency of 6,000 Hz, but the sensitivity is only 5 pm/g. The pictorial diagrams of the two sensors are shown in Figure 30(a) and 30(b), respectively.

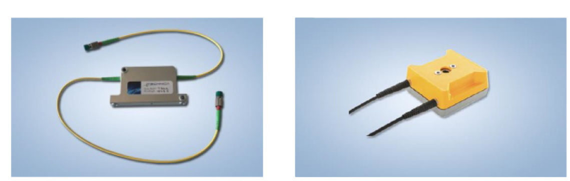
The eight commercial sensors described above are FBG acceleration sensors based on the wavelength modulation principle. When the wavelength detecting FBG acceleration sensor is excited by the external vibration, the light wave signal satisfying the Bragg reflection condition is received and demodulated into the wavelength signal by the FBG wavelength demodulator. Therefore, the center wavelength drift of the FBG measured by the wavelength demodulator can be used to reverse the external acceleration information.

In summary, the basic information of the commercial accelerometers is shown in Table 6.

6. Discussions

The purpose of this paper is to present the state of the art for FBG acceleration sensing technologies from two aspects principle of the measurement dimension and the principle of the sensing configuration design. In the past decade, the FBG acceleration sensors have been mainly completely packaged or two-point packaged. The grating region with the removed coating layer is encapsulated on the elastomer surface by adhesive, which is simple to operate. However, the sensor performance is easily affected by adhesive and elastomer. For this reason, many scholars use different sensitization methods

Figure 30 Pictorial diagram of the commercial sensor produced by TECHNICA



(a) (b)

Notes: (a) "T320"; (b) "T310

Table 6 Basic information of the commercial accelerometers

Model	Manufacturing company	Working range (Hz)	Resonant frequency (Hz)	Sensitivity (pm/g)	Signal transmitted by sensor
os7100	MOI	DC-300	~700	~16	Light wavelength
FS6500	Fiber Sensing	0–50	430	75	Light wavelength
SmartAccel-40g	Gavea Sensors	0–1000	/	4–10	Light wavelength
4590	B&K	DC-1000	3,100	20	Light wavelength
GS-TM-ZD-II	JSKJ	/	/	120	Light wavelength
KNPAC-1	OPMATERIAL	0.5–30	/	500	Light wavelength
T320	TECHNICA	0–600	1,748	79.46	Light wavelength
T310	TECHNICA	0–2000	6,000	5	Light wavelength

or special structures to improve the sensitivity of the sensor or broaden the working frequency band of the sensor, which improves the overall performance of the sensor. The two ends of the pre-stretched fiber are encapsulated on the inertial object and matrix by adhesive, which avoids the generation of chirp. However, as the fiber is directly used as the elastomer, it is easy to break. For this reason, many scholars use special optical fibers with higher strength or elastomer structures, such as the elastic diaphragm, elastic tube and elastic shell to improve the overall performance of sensors.

The one-dimensional FBG accelerometer requires less measuring elements and sensors based on different structures can be used to meet the requirements of different measuring fields. However, they are not suitable for the multi-dimensional measurement field. To realize two-dimensional or even three-dimensional measurement, the design of the sensor needs to consider the problems of the structural characteristics, temperature compensation and vibration cross-coupling.

The sensitivity and resonance frequency are two important indexes of the acceleration sensor. The highest resonant frequency of reported FBG-based acceleration sensors so far is only a few kilohertz, which is still far from the hundreds of thousands of Hertz resonant frequency of the traditional piezoelectric acceleration sensor. Moreover, the resonance frequency and sensitivity of most FBG acceleration sensors are mutually restricted. Therefore, the following research areas will be strengthened in the future:

- *Common single-mode fiber grating of the low cost and high utilization rate*: At present, most FBG acceleration sensors take the common single-mode fiber grating as the measuring element. Then the high cost and low utilization rate of the fiber grating make the manufacturing cost of the sensor increase greatly. Therefore, it is necessary to optimize the preparation method of the fiber grating and improve the utilization rate of the fiber grating.
- *High sensitivity and strength special fiber grating*: When the common single-mode fiber grating is completely encapsulated on the surface of the elastomer, the sensitivity and resonance frequency of the sensor will be restricted by the structure. The fiber is easy to break when the two-point encapsulation method is used. At present, some special fiber gratings with high sensitivity and strength are prepared on the high-performance fibers, such as the polymer fiber, polarization-maintaining fiber, micro-structure fiber, photonic crystal fiber and D-shaped fiber. So, we can do more research in this area.
- *Multi-core fiber grating for measuring single-parameter multi-dimensional information or multi-parameter information*: If a certain number of common single-mode fiber gratings and special elastic structures are used to detect two-dimensional or even three-dimensional vibration information traditionally, the difficulty of the sensor fabrication will be greatly deepened and the detection performance of the sensor may be affected by the deviation of grating packaging technology and placement. At present, it has become a hot spot to use multi-core fiber gratings to measure single-parameter multi-dimensional or multi-parameter information, so we can fabricate high-performance multi-dimensional acceleration or multi-parameter measurement sensors around the gratings.
- *Demodulating equipment of low cost, small volume and high sampling frequency*: The expensive demodulation equipment makes it difficult to market the sensor and the large size demodulation equipment limits the development of FBG wireless sensing technology and the demodulation equipment with low sampling frequency cannot meet the monitoring needs of high-frequency applications. Therefore, it is imperative to develop a demodulator with low cost, small volume and high sampling frequency.

7. Conclusions

With the continuous development of FBG sensing technology, there are more and more research studies on FBG acceleration sensors across the world. The development of various new materials and structures makes the FBG acceleration sensor applied in more occasions. This paper introduces the principle, classification and research status of the FBG based acceleration sensor and the future work in this field is discussed. In a word, by continuously solving one technical problem after another of the FBG acceleration sensor, the existing engineering practice shows that the performance of the FBG acceleration sensor is obviously better than that of the acceleration sensor based on the traditional electromagnetic principle. However, with the development of The Times, more and more new requirements will be put forward for the acceleration sensor. Then the research of the FBG acceleration sensor is in the ascendant.

References

Abushagur, O.M., Abushagur, M.A.G. and Narayanan, K. (2005), "Novel three-axes fiber Bragg grating accelerometer", *Optomechanics 2005 International Society for Optics and Photonics*.

Alessandro, A.D., Scudero, S. and Vitale, G. (2019), "A review of the capacitive MEMS for seismology", *SENSORS*, Vol. 19 No. 14.

Antunes, P., Varum, H. and André, P. (2010), "Uniaxial fiber Bragg grating accelerometer system with temperature and cross axis insensitivity", *Measurement*, Vol. 44 No. 1, pp. 55-59.

Antunes, P., Travanca, R., Rodrigues, H., Melo, J., Jara, J., Varum, H. and Andre, P. (2012), "Dynamic structural health monitoring of slender structures using optical sensors", *Sensors*, Vol. 12 No. 5, pp. 6629-6644.

Basumallick, N., Biswas, P., Dasgupta, K. and Bandyopadhyay, S. (2013), "Design optimization of fiber Bragg grating accelerometer for maximum sensitivity", *Sensors and Actuators A: Physical*, Vol. 194, pp. 31-39.

Basumallick, N., Bhattacharya, S., Dey, T.K., Biswas, P. and Bandyopadhyay, S. (2020), "Wideband fiber Bragg grating accelerometer suitable for health monitoring of electrical machines", *IEEE Sensors Journal*, Vol. 20 No. 24, pp. 14865-14872.

Basumallick, N., Chatterjee, I., Biswas, P., Dasgupta, K. and Bandyopadhyay, S. (2011), "Fiber Bragg grating accelerometer with enhanced sensitivity", *Sensors and Actuators A: Physical*, Vol. 173 No. 1, pp. 108-115.

Basumallick, N., Biswas, P., Chakraborty, R., Chakraborty, S., Dasgupta, K. and Bandyopadhyay, S. (2016), "Fibre Bragg grating based accelerometer with extended bandwidth", *Measurement Science and Technology*, Vol. 27 No. 3.

Chen, W.G., Wang, J.X., Wan, F. and Wang, P.Y. (2019), "Review of optical fibre sensors for electrical equipment characteristic state parameters detection", *HIGH Voltage*, Vol. 4 No. 4, pp. 271-281.

Costa Antunes, P.F.D., Lima, H.F.T., Alberto, N.J., Rodrigues, H., Pinto, P.M.F., Pinto, J.D.L., Nogueira, R.N., Varum, H., Costa, A.G. and Andre, P.S. (2009), "Optical fiber accelerometer system for structural dynamic monitoring", *IEEE SENSORS Journal*, Vol. 9 No. 11, pp. 1347-1354.

Costa Antunes, P.F., Marques, C.A., Varum, H. and Andre, P.S. (2012), "Biaxial optical accelerometer and high-angle inclinometer with temperature and cross-axis insensitivity", *IEEE SENSORS Journal*, Vol. 12 No. 7, pp. 2399-2406.

Dai, Y.T., Yin, G.L., Liu, B., Xu, G. and Karanja, J.M. (2015), "Medium-high frequency FBG accelerometer with integrative matrix structure", *APPLIED Optics*, Vol. 54 No. 11, pp. 3115-3121.

Dong, K., Dai, Y.T., Yin, G.L., Hu, P.F. and Zhou, M. (2017), "Medium-low frequency fiber optic acceleration sensor based on symmetrical gemel and its optimization design", *Journal of Optoelectronics· Laser*, Vol. 28 No. 1, pp. 6-11.

Dreyer, U.J., Mezzadri, F., Dutra, G., da Silva, T., Bavastri, C.A., da Silva, E.V., Martelli, C. and Cardozo da Silva, J.C. (2018), "Quasi-distributed optical fiber transducer for simultaneous temperature and vibration sensing in high-power generators", *IEEE SENSORS Journal*, Vol. 18 No. 4, pp. 1547-1554.

Fu, D.X., Zhang, Y.N., Zhang, A.Z., Han, B., Wu, Q.L. and Zhao, Y. (2019), "Novel fiber grating for sensing applications", *Physica Status Solidi A-Applications and Materials Science*, Vol. 216 No. 6.

Gao, X.Q., Wang, Y.J., Yuan, B., Yuan, Y.Q., Dai, Y.W. and Xu, G. (2013), "Low-cost vibration sensor based on dual fiber Bragg gratings and light intensity measurement", *APPLIED Optics*, Vol. 52 No. 27, pp. 6782-6787.

Gautam, A., Kumar, A. and Priye, V. (2019), "Microseismic wave detection in coal mines using differential optical power measurement", *OPTICAL Engineering*, Vol. 58 No. 5.

Giacci, F., Dellea, S. and Langfelder, G. (2017), "Signal integrity in capacitive and piezoresistive single- and multi-axis MEMS gyroscopes under vibrations", *MICROELECTRONICS Reliability*, Vol. 75, pp. 59-68.

Guo, Y.X. (2014), "Research on monitoring technology and application of high-steep slope and rockfall based on fiber Bragg grating", Ph.D. dissertation, Wuhan University of Technology, Wuhan.

Guo, Y.X., Xiong, L. and Liu, H.H. (2019), "Research on the durability of metal-packaged fiber Bragg grating sensors", *IEEE PHOTONICS TECHNOLOGY Letters*, Vol. 31 No. 7, pp. 525-528.

Guo, T., Zhang, T.X., Li, Y.Z. and Qiao, X.G. (2020), "Highly sensitive FBG seismometer with a 3D-printed hexagonal configuration", *Journal of Lightwave Technology*, Vol. 38 No. 16, pp. 4588-4595.

Guo, Y.X., Zhang, D.S., Li, J.Y. and Zhu, F.D. (2012), "Two dimensional fiber Bragg grating accelerometer", *Chinese Journal of Lasers*, Vol. 39 No. 12, pp. 198-204.

Guo, Y.X., Li, C., Zhou, X.L., Jiang, L. and Liu, H.H. (2020), "Wide-Range fiber Bragg grating tilt sensor based on a cam structure", *IEEE SENSORS Journal*, Vol. 20 No. 9, pp. 4740-4748.

Guo, T., Zhang, X.L., Liu, X.R., Chen, S.H. and Liu, T.Y. (2009), "A new type of fiber Bragg grating based seismic geophone", *APPLIED Geophysics*, Vol. 6 No. 1, pp. 84-92.

Guo, Y.X., Zhang, D.S., Zhou, Z.D., Xiong, L. and Deng, X.W. (2013a), "Welding-packaged accelerometer based on metal-coated FBG", *Chinese Optics Letters*, Vol. 11 No. 7.

Guo, Y.X., Zhang, D.S., Zhou, Z.D., Xiong, L. and Zhu, F.D. (2013b), "Research progress in Fiber-Bragg-Grating accelerometer", *Laser & Optoelectronics Progress*, Vol. 50 No. 6, pp. 5-12.

Guo, Y.X., Zhang, D.S., Zhou, Z.D., Zhu, F.D., Xiong, L. and Li, T.L. (2013c), "Cantilever based FBG vibration transducer with sensitization structure", *Optoelectronics Letters*, Vol. 9 No. 6, pp. 410-413.

Gutiérrez, N., Galvín, P. and Lasagni, F. (2018), "Low weight additive manufacturing FBG accelerometer: design, characterization and testing", *Measurement*, Vol. 117, pp. 295-303.

Han, X.Y., Wen, H.Q., Liu, S., Xiong, Y.C. and Luo, Z.H. (2017), "Dual-fiber-Bragg gratings accelerometer for the detection of geosound caused by debris flow", *Optical Engineering*, Vol. 56 No. 5, p. 056104.

Hou, Y.F., Lu, Z.M., Zhang, W.T. and Li, F. (2012), "Design development of probe of three-component fiber-optic acceleration sensor", *Transducer and Microsystem Technologies*, Vol. 31 No. 8, pp. 1-4, 8.

Jiang, Q. and Yang, M. (2012), "A high sensitivity vector accelerometer based on tri-axial fiber Bragg grating", *Optica Applicata*, Vol. 42 No. 4, pp. 901-912.

Jiang, Q. and Yang, M. (2013), "Simulation and experimental study of a three-axis fiber Bragg grating accelerometer based on the pull-push mechanism", *Measurement Science and Technology*, Vol. 24 No. 11.

Jiang, M.S., Sui, Q.M. and Feng, D.J. (2009), "Research and realization of novel FBG vibration sensor", *Instrument Technique and Sensor*, Vol. 7 No. 6, pp. 1-3.

Jiang, Q., Jiang, H., Sui, Q.M. and Wu, J.P. (2008), "Three-component fiber Bragg grating vibration sensor", C.N. Patent 201043915.

Jiang, G.Y., Nie, D.X., Liu, H.B., Deng, J.G., Li, W.Z. and Zhou, J.H. (2014), "On-line vibration monitoring system of oil-immersed transformer with fiber Bragg grating sensor", C.N. Patent 203772406U.

Kamenev, O.T., Kulchin, Y.N., Petrov, Y.S., Khiznyak, R.V. and Romashko, R.V. (2016), "Fiber-optic seismometer on the basis of Mach-Zehnder interferometer", *Sensors and Actuators A: Physical*, Vol. 244, pp. 133-137.

Khan, M.M., Panwar, N. and Dhawan, R. (2014), "Modified cantilever beam shaped FBG based accelerometer with self-temperature compensation", *Sensors and actuators A: Physical*, Vol. 205, pp. 79-85.

Kishore, P. (2018), "FBG based seismic vibration sensor with inverted spring-mass system", *Journal of Optoelectronics and Advanced Materials*, Vol. 20 No. 11-12, pp. 601-609.

Kordas, K. and Pitkanen, O. (2019), "Piezoresistive carbon foams in sensing applications", *Frontiers in Materials*, Vol. 6.

Kuang, Y., Guo, Y.X., Xiong, L. and Liu, W.L. (2018), "Packaging and temperature compensation of fiber Bragg grating for strain sensing: a survey", *Photonic Sensors*, Vol. 8 No. 4, pp. 320-331.

Kuhn, G.G., Sousa, K.M., Martelli, C., Bavastri, C.A. and da Silva, J.C.C. (2020), "Embedded FBG sensors in carbon fiber for vibration and temperature measurement in power transformer iron core", *IEEE Sensors Journal*, Vol. 20 No. 22, pp. 13403-13410.

Li, G.L. and Liu, X.J. (2014), "Design of fiber Bragg grating acceleration sensing probe based on dual simply supported beams", *Piezoelectrics & Acoustooptics*, Vol. 36 No. 1, pp. 32-34.

Li, T.L., Tan, Y.G. and Zhou, Z.D. (2016), "A fiber Bragg grating sensing-based micro-vibration sensor and its application", *Sensors*, Vol. 16 No. 4.

Li, W., Zhou, Z.D., Huang, J. and Tan, Y.G. (2013), "FBG-based non-contact vibration measurement and experimental study", *International Journal of precision engineering and Manufacturing*, Vol. 14 No. 9, pp. 1577-1581.

Li, K., Chan, T.H.T., Yau, M.H., Thambiratnam, D.P. and Tam, H.Y. (2014), "Biaxial fiber Bragg grating accelerometer using axial and transverse forces", *IEEE Photonics Technology Letters*, Vol. 26 No. 15, pp. 1549-1552.

Li, T.L., Tan, Y.G. and Zhou, Z.D. (2017a), "String-type based two-dimensional fiber Bragg grating vibration sensing principle and structure optimization", *Sensors and Actuators A: Physical*, Vol. 259, pp. 85-95.

Li, K., Chan, T.H.T., Yau, M.H., Thambiratnam, D.P. and Tam, H.Y. (2015), "Fiber Bragg grating accelerometer based on a transversely rotating stick", *Optik*, Vol. 126 No. 23, pp. 4337-4341.

Li, L., Dong, X.Y., Shao, L.Y., Zhao, C.L. and Sun, Y.L. (2010), "Temperature-independent acceleration measurement with a strain-chirped fiber Bragg grating", *Optoelectronics and Advanced Materials-Rapid Communications*, Vol. 4 No. 7, pp. 943-946.

Li, L., Dong, X.Y., Zhou, W.J. and Sun, Y.L. (2009), "Temperature-independent accelerometer with a strain-chirped fiber Bragg grating", *2009 Asia Communications and Photonics conference and Exhibition*, Shanghai, pp. 1-7.

Li, T.L., Tan, Y.G., Xia, P. and Zhou, Z.D. (2017b), "Paralleled structure-based string-type fiber Bragg grating acceleration sensor", *IEEE Sensors Journal*, Vol. 17 No. 5, pp. 1325-1332.

Li, T.L., Tan, Y.G., Zhou, Z.D. and Qin, W. (2015), "Pasted type distributed two-dimensional fiber Bragg grating vibration sensor", *Review of Scientific Instruments*, Vol. 86 No. 7.

Li, T.L., Tan, Y.G., Zhou, Z.D. and Zheng, K. (2016), "A non-contact FBG vibration sensor with double differential temperature compensation", *Optical Review*, Vol. 23 No. 1, pp. 26-32.

Li, T.L., Shi, C.Y., Tan, Y.G., Li, R.Y. and Zhou, Z.D. (2017c), "A diaphragm type fiber Bragg grating vibration sensor based on transverse property of optical fiber with temperature compensation", *IEEE Sensors Journal*, Vol. 17 No. 4, pp. 1021-1029.

Li, T.L., Tan, Y.G., Han, X., Zheng, K. and Zhou, Z.D. (2017d), "Diaphragm based fiber Bragg grating acceleration sensor with temperature compensation", *Sensors*, Vol. 17 No. 12.

Li, T.L., Tan, Y.G., Zhou, Z.D., Cai, L. and Li, R.Y. (2015a), "Research on pasted FBG-based accelerometer's sensitization process method and its characteristics", *IEICE Electronics Express*, Vol. 12 No. 17.

Li, T.L., Tan, Y.G., Zhou, Z.D., Cai, L. and Wei, L. (2015d), "Turbine rotor dynamic balance vibration measurement based on the non-contact optical fiber grating sensing", *IEICE Electronics Express*, Vol. 12 No. 12.

Li, W., Jiang, D.Z., Yu, L.L., Li, H.C. and Liu, Z. (2019), "A novel miniaturized fiber Bragg grating vibration sensor", *IEEE Sensors Journal*, Vol. 19 No. 24, pp. 11932-11940.

Li, W., Yu, L.L., Wang, J.J., Jiang, D.Z. and Qin, L. (2019), "An FBG-sensing two-dimensional vibration sensor based on multi-axis flexure hinge", *IEEE Sensors Journal*, Vol. 19 No. 10, pp. 3698-3710.

Li, T.L., Tan, Y.G., Liu, Y., Qu, Y.Z., Liu, M.Y. and Zhou, Z.D. (2015b), "A fiber Bragg grating sensing based triaxial vibration sensor", *Sensors*, Vol. 15 No. 9, pp. 24214-24229.

Li, K., Chan, T.H.T., Yau, M.H., Nguyen, T., Thambiratnam, D.P. and Tam, H.Y. (2013), "Very sensitive fiber Bragg grating accelerometer using transverse forces with an easy over-range protection and low cross axial sensitivity", *APPLIED Optics*, Vol. 52 No. 25, pp. 6401-6410.

Li, T.L., Tan, Y.G., Li, W., Zhou, Z.D., Zheng, K. and Guo, Y.X. (2014), "A non-contact fiber Bragg grating vibration sensor", *Review of scientific Instruments*, Vol. 85 No. 1.

Li, T.L., Tan, Y.G., Zhou, Z.D., Cai, L., Liu, S., He, Z.T. and Zheng, K. (2015c), "Study on the non-contact FBG vibration sensor and its application", *Photonic Sensors*, Vol. 5 No. 2, pp. 128-136.

Liang, L., Li, D.X., Chou, L. and Xu, G. (2016), "An FBG acceleration sensor based on flexure hinge", *Journal of Optoelectronics· Laser*, Vol. 27 No. 4, pp. 347-352.

Linessio, R.P., dos Santos Tavares, L.H., da Silva, T., de Oliveira, V., Bavastri, C.A., da Costa Antunes, P.F., D. and Silva, J.C.C. (2019), "Biaxial optical accelerometer based on ultra-high numerical aperture fiber", *IEEE Sensors Journal*, Vol. 19 No. 10, pp. 3690-3697.

Linessio, R.P., Sousa, K.D.M., da Silva, T., Bavastri, C.A., da Costa Antunes, P.F., D. and Silva, J.C.C. (2016), "Induction motors vibration monitoring using a biaxial optical fiber accelerometer", *IEEE Sensors Journal*, Vol. 16 No. 22, pp. 8075-8082.

Liu, B., Niu, W.C., Yang, Y.F., Luo, J.H. and Cao, Y. (2006), "A novel fiber Bragg grating accelerometer", *Chinese Journal of Scientific Instrument*, Vol. 27 No. 1, pp. 42-44.

Liu, Q.P., He, X., Qiao, X.G., Sun, T. and Grattan, K.T.V. (2019), "Design and modeling of a high sensitivity fiber Bragg grating-based accelerometer", *IEEE SENSORS Journal*, Vol. 19 No. 14, pp. 5439-5445.

Liu, Q.P., Qiao, X.G., Jia, Z.A., Fu, H.W. and Gao, H. (2014), "Large frequency range and high sensitivity fiber Bragg grating accelerometer based on double diaphragms", *IEEE Sensors Journal*, Vol. 14 No. 5, pp. 1499-1504.

Liang, Q.L., Sun, Q.Z., Xu, J., Yu, L. and Zhang, M.L. (2012), "A new fiber optic accelerometer based on fiber Bragg grating", *Photonics and Optoelectronics Meetings (POEM) 2011: Optoelectronic Sensing and Imaging*, p. 83320D.

Liu, F., Gao, S.Q., Niu, S.H., Zhang, Y., Guan, Y.W., Gao, C. H. and Li, P. (2018), "Optimal design of high-g MEMS piezoresistive accelerometer based on timoshenko beam theory", *Microsystem Technologies*, Vol. 24 No. 2, pp. 855-867.

Masek, V., Cada, M., Cook, A., Nan, W. and Li, D. (2011), ""Fibre optic based 3-D accelerometer design", *Sensors Applications Symposium (SAS), 2011 IEEE*, pp. 123-126.

Morikawa, S.R.K., Ribeiro, A.S., Regazzi, R.D., Valente, L.C.G. and Braga, A.M.B. (2002), "Triaxial Bragg grating accelerometer", in *Optical Fiber Sensors Conference*, pp. 95-98.

Muller, M.S., Buck, T.C. and Koch, A.W. (2009), "Fiber bragg grating-based acceleration sensor", *2009 International Symposium on Optomechatronic Technologies*, Istanbul, pp. 127-132.

Munendhar, P. and Khijwania, S.K. (2013), "Two dimensional fiber Bragg grating based vibration sensor for structural health monitoring", *AIP Conference Proceedings*, pp. 1324-1326.

Nan, Q.M. and Li, S. (2016), "Study on 3D CFBG vibration sensor and its application", *Photonic Sensors*, Vol. 6 No. 1, pp. 90-96.

Nan, Q.M. and Song, L. (2014), "Research on 3D FBG accelerometer and demodulation method", *Chinese Optics Letters*, Vol. 12.

Nan, Q.M. and Zou, C.M. (2009), "Study on FBG vibration sensor", *Symposium on Photonics and Optoelectronics*, pp. 1-4.

Nan, Q.M., Li, S., Yao, Y.Q., Li, Z.Y., Wang, H.H., Wang, L.X. and Sun, L.Z. (2019), "A novel monitoring approach for train tracking and incursion detection in underground structures based on Ultra-Weak FBG sensing array", *Sensors*, Vol. 19 No. 12.

Ni, K., Chan, C.C., Dong, X.Y. and Li, L. (2013), "Temperature-independent accelerometer using a fiber Bragg grating incorporating a biconical taper", *Optical Fiber Technology*, Vol. 19 No. 5, pp. 410-413.

Panda, O.P., Nayak, J. and Asokan, S. (2019), "Design and validation of a novel high sensitivity self-temperature compensated fiber Bragg grating accelerometer", *IEEE SENSORS Journal*, Vol. 19 No. 15, pp. 6197-6204.

Panda, O.P., Thomas, J., Nayak, J. and Asokan, S. (2019), "Double-L Cantilever-based fiber Bragg grating accelerometer", *IEEE SENSORS Journal*, Vol. 19 No. 23, pp. 11247-11254.

Pramanik, R. and Arockiarajan, A. (2019), "Effective properties and nonlinearities in 1-3 piezocomposites: a comprehensive review", *SMART MATERIALS aND Structures*, Vol. 28 No. 10.

Qiu, L., Liang, L., Li, D.X. and Xu, G. (2017), "Theoretical and experimental study on FBG accelerometer based on multi-flexible hinge mechanism", *Optical Fiber Technology*, Vol. 38, pp. 142-146.

Ramos, M.A.C. and Romero, G.E.S. (2017), "Cantilever beam vibration sensor based on the axial property of fiber Bragg grating", *Smart Structures and Systems*, Vol. 19 No. 6, pp. 625-631.

Rong, Q.Z. and Qiao, X.G. (2019), "FBG for oil and gas exploration", *Journal of Lightwave Technology*, Vol. 37 No. 11, pp. 2502-2515.

Sahota, J.K., Gupta, N. and Dhawan, D. (2020), "Fiber Bragg grating sensors for monitoring of physical parameters: a comprehensive review", *Optical Engineering*, Vol. 59 No. 6.

Shi, C.Z., Zeng, N. and Ho, H.L. (2003), "Cantilever optical vibrameter by use of fiber Bragg grating", *Optical Engineering*, Vol. 42 No. 11, pp. 3179-3181.

Shivashankar, P. and Gopalakrishnan, S. (2020), "Review on the use of piezoelectric materials for active vibration", *Smart Materials and Structures*, Vol. 29 No. 5.

Song, H., Wang, Q.D., Liu, M.Y. and Cai, Q.H. (2020), "A novel fiber Bragg grating vibration sensor based on orthogonal flexure hinge structure", *IEEE SENSORS Journal*, Vol. 20 No. 10, pp. 5277-5285.

Stefani, A., Andresen, S., Yuan, W., Rasmussen, N.H. and Bang, O. (2012), "High sensitivity polymer optical Fiber-Bragg-Grating-based accelerometer", *IEEE Photonics Technology Letters*, Vol. 24 No. 9, pp. 763-765.

Sun, L.M., Shen, Y. and Cao, C.G. (2009), "A novel FBG-based accelerometer with high sensitivity and temperature self-compensation", *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2009*.

Sun, R.J., Sun, L.M., Sun, Z., Dan, D.H. and Liu, X.H. (2007), "Study on a novel fiber Bragg grating vibration sensor", *Acta Photonica Sinica*, Vol. 36 No. 1, pp. 63-67.

Sun, L.Q., Dong, B., Wang, Y.X., Lally, E. and Wang, A.B. (2008), "Temperature-insensitive fibre-optic acceleration sensor based on intensity-referenced fibre Bragg gratings", *Chinese Physics Letters*, Vol. 25 No. 10, pp. 3593-3596.

Talebinejad, I., Fischer, C. and Ansari, F. (2009), "Low frequency fiber optic accelerometer for civil structural health monitoring", Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2009, p. 729412.

Tiwari, U.K., Saini, T.S., Negi, V., Pandey, A., Garg, H. and Sinha, R.K. (2019), "Design and development of a field deployable packaged fiber Bragg grating-based accelerometer", *Optical Engineering*, Vol. 58 No. 1.

Udos, W., Lee, Y.S., Lim, K.S., Ong, Z.C., Zaini, M.K.A. and Ahmad, H. (2020), "Signal enhancement of FBG-based cantilever accelerometer by resonance suppression using magnetic damper", *Sensors and Actuators A-Physical*, Vol. 304.

Wang, K. (2015), "Enhanced-sensitivity fiber grating acceleration sensor design", *Instrument Technique and Sensor*, Vol. 16 No. 1, pp. 10-12.

Wang, C., Lu, Q.Y. and Cheng, L.J. (2013), "Novel type of temperature self-compensating acceleration transducer based on OFBG", *IEEE Sensors Journal*, Vol. 13 No. 8, pp. 3012-3013.

Wang, X.F., Guo, Y.X. and Xiong, L. (2018a), "Hybrid fiber Bragg grating sensor for vibration and temperature monitoring of a train bearing", *Chinese Optics Letters*, Vol. 16 No. 7.

Wang, X.F., Guo, Y.X., Xiong, L. and Wu, H. (2018b), "High-frequency optical fiber Bragg grating accelerometer", *IEEE Sensors Journal*, Vol. 18 No. 12, pp. 4954-4960.

Wang, Y.J., Wang, R., Li, F. and Liu, Y.L. (2009), "A new fiber Bragg grating based accelerometer", SPIE.

Wang, J., Wei, G.Q., Shi, B. and Yan, J.F. (2012), "A three-component fiber Bragg grating vibration sensor", C.N. Patent 102840908A.

Wang, Y.J., Yuan, Y.Q. and Liang, L. (2015), "A low-cost acceleration monitoring system based on dual fiber Bragg gratings", *Optik – International Journal for Light and Electron Optics*, Vol. 126 No. 19, pp. 1803-1805.

Wang, H.L., Zhou, H.Q., Gao, H., Feng, D.Q. and Fan, W. (2013), "Fiber grating acceleration vibration sensor with double uniform strength cantilever beams", *Journal of Optoelectronics· Laser*, Vol. 24 No. 4, pp. 635-641.

Wang, J., Peng, G.D., Hu, Z.L., Yang, H.Y. and Hu, Y.M. (2015a), "Design and analysis of a high sensitivity FBG accelerometer based on local strain amplification", *IEEE SENSORS Journal*, Vol. 15 No. 10, pp. 5442-5449.

Wang, J.F., Yu, Y., Chen, Y., Luo, H. and Zhou, M. (2015b), "Research of a double fiber Bragg gratings vibration sensor with temperature and cross axis insensitive", *Optik*, Vol. 126 Nos 7/8, pp. 749-753.

Wang, J., Zeng, Y.J., Lin, C.Y., Hu, Z.L. and Peng, G.D. (2016), "A miniaturized FBG accelerometer based on a thin polyurethane shell", *IEEE SENSORS Journal*, Vol. 16 No. 5, pp. 1210-1216.

Wang, S.L., Xiang, G.H., Hu, M.L., Qiao, X.G. and Wang, J. (2011), "Design of a novel FBG vibration sensor", *Journal of Optoelectronics· Laser*, Vol. 22 No. 4, pp. 515-519.

Wang, J.J., Wei, L., Li, R.Y., Liu, Q. and Yu, L.L. (2017), "An FBG-Based 2-D vibration sensor with adjustable sensitivity", *IEEE SENSORS Journal*, Vol. 17 No. 15, pp. 4716-4724.

Wang, J.Y., Hu, B.X., Li, W., Song, G.D., Jiang, L. and Liu, T.Y. (2016), "Design and application of fiber Bragg grating (FBG) geophone for higher sensitivity and wider frequency range", *Measurement*, Vol. 79, pp. 228-235.

Weng, Y.Y., Qiao, X.G., Feng, Z.Y., Hu, M.L. and Zhang, J. H. (2011), "Compact FBG diaphragm accelerometer based on L-shaped rigid cantilever beam", *Chinese Optics Letters*, Vol. 9 No. 10.

Weng, Y.Y., Qiao, X.G., Guo, T., Hu, M.L. and Zhong, Z.Y. (2012), "A robust and compact fiber Bragg grating vibration sensor for seismic measurement", *IEEE Sensors Journal*, Vol. 12 No. 4, pp. 800-804.

Xiang, L.H., Jiang, Q., Li, Y.B. and Song, R. (2016), "Design and experimental research on cantilever accelerometer based on fiber Bragg grating", *OPTICAL Engineering*, Vol. 55 No. 6.

Xie, Z.C., Tan, Y.G., Huang, B., Jiang, D.Z. and Liu, H. (2020), "High sensitivity fiber Bragg grating acceleration sensor based on rigid hinge", *IEEE Sensors Journal*, Vol. 20 No. 15, pp. 8223-8231.

Xiong, L., Jiang, G.Z., Guo, Y.X., Kuang, Y. and Liu, H.H. (2019), "Investigation of the temperature compensation of FBGs encapsulated with different methods and subjected to different temperature change rates", *Journal of Lightwave Technology*, Vol. 37 No. 3, pp. 917-926.

Xiong, L., Guo, Y.X., Jiang, G.Z., Zhou, X.L., Jiang, L. and Liu, H.H. (2020), "A six-dimensional force/torque sensor based on fiber Bragg gratings with low coupling", *IEEE Transactions on Industrial Electronics*, doi: 10.1109/TIE.2020.2982107.

Xu, H.B., Li, F., Gao, Y. and Wang, W.W. (2020), "Simultaneous measurement of tilt and acceleration based on FBG sensor", *IEEE Sensors Journal*, Vol. 20 No. 24, pp. 14857-14864.

Yan, B. and Liang, L. (2020), "A novel fiber Bragg grating accelerometer based on parallel double flexible hinges", *IEEE SENSORS Journal*, Vol. 20 No. 9, pp. 4713-4718.

Yang, M. and Jiang, Q. (2013), "An accelerometer sensor finite element analysis and design based on fiber Bragg grating", *Eighth International Symposium on Precision Engineering Measurement and Instrumentation*, p. 87592O.

Yao, K., Lin, Q.J., Jiang, Z.D., Zhao, N., Peng, G.D., Tian, B., Jia, W.Y. and Yang, P. (2019), "Design and analysis of a combined strain-vibration-temperature sensor with two fiber Bragg gratings and a trapezoidal beam", *Sensors*, Vol. 19 No. 16.

Yao, K., Lin, Q.J., Jiang, Z.D., Zhao, N., Tian, B., Shi, P. and Peng, G.D. (2018), "Modeling and analysis of a combined stress-vibration fiber Bragg grating sensor", *Sensors*, Vol. 18 No. 3.

Ye, T., Liang, D.K., Zeng, J., Zhang, S.H. and Sun, W. (2012), "Study on optical fiber grating vibration sensor based on bow beam sensitive characteristic", *Chinese Journal of Scientific Instrument*, Vol. 33 No. 1, pp. 139-145.

Yin, G.L., Xu, G., Dai, Y.T., Zhao, Q.C. and Liu, B. (2014), "Diaphragm accelerometer based on double fiber Bragg gratings", *Journal of Wuhan University of Technology*, Vol. 36 No. 6, pp. 131-134.

Yüksel, K., Kinet, D., Moeyaert, V., Kouroussis, G. and Caucheteur, C. (2018), "Railway monitoring system using optical fiber grating accelerometers", *SMART Materials and Structures*, Vol. 27 No. 10.

Zhang, D.S., Guo, Y.X. and Meng, H. (2012), "Fiber bragg grating sensor for three dimensional acceleration measurement", C.N. Patent 102495235A.

Zhang, Q., Zhu, T., Zhang, J.D. and Chiang, K.S. (2013), "Micro-fiber-based FBG sensor for simultaneous measurement of vibration and temperature", *IEEE Photonics Technology Letters*, Vol. 25 No. 18, pp. 1751-1753.

Zhang, J.H., Qiao, X.G., Feng, Z.Y., Weng, Y.Y. and Yang, Y. (2011a), "A compact metal bellows-based fiber Bragg grating accelerometer for structural health monitoring", 2011 *Symposium on Photonics and Optoelectronics*, pp. 1-4.

Zhang, J.H., Qiao, X.G., Hu, M.L., Feng, Z.Y., Gao, H., Yang, Y. and Zhou, R. (2011b), "Proposal of metal bellows-based fiber Bragg grating accelerometer", *Chinese Optics Letters*, Vol. 9 No. 9.

Zhang, X.Z., Sun, F., Jiang, J.F., Feng, M., Wang, S., Fan, X.J., Yang, Y.N. and Liu, T.G. (2019), "High-precision FBG demodulation using amplitude ratio curve with sharp peak", *Optical Fiber Technology*, Vol. 47, pp. 7-14.

Zhang, X.L., A, F.X., Li, S.J., Wang, M., Wang, L.J., Song, Z.Q., Sun, Z.H., Qi, H.F., Wang, C. and Peng, G.D. (2014b), "A high performance compact vibration sensor based on fiber Bragg grating", *Chinese Optics Letters*, Vol. 12.

Zhang, X.L., Liu, X.M., Zhang, F.X., Sun, Z.H., Min, L., Li, S.J., Jiang, S.D., Li, M., Wang, C. and Ni, J.S. (2018), "Reliable high sensitivity FBG geophone for low frequency seismic acquisition", *Measurement*, Vol. 129, pp. 62-67.

Zhang, X.L., Rong, Q.Z., Sun, H., Yang, S., Yuan, L.T. and Hu, M.L. (2014a), "Low-frequency fiber Bragg grating accelerometer based on a double-semicircle cantilever", *Optical Fiber Technology*, Vol. 20 No. 3, pp. 190-193.

Zhang, Z.Y., Liu, C.T., Li, H.C., He, Z.X. and Zhao, X.F. (2017a), "Optical fiber grating vibration sensor for vibration monitoring of hydraulic pump", *PHOTONIC Sensors*, Vol. 7 No. 2, pp. 140-147.

Zhang, Y.S., Qiao, X.G., Liu, Q.P., Yu, D.K. and Gao, H. (2015), "Study on a fiber Bragg grating accelerometer based on compliant cylinder", *Optical Fiber Technology*, Vol. 26, pp. 229-233.

Zhang, Y.S., Zhang, W.G., Zhang, Y.X., Chen, L., Yan, T.Y., Wang, S., Yu, L. and Li, Y.P. (2017b), "2-D medium-high frequency fiber Bragg gratings accelerometer", *IEEE Sensors Journal*, Vol. 17 No. 3, pp. 614-618.

Zhou, W.J., Dong, X.Y., Jin, Y.X. and Zhao, C.L. (2009a), "Cantilever-based FBG sensor for temperature-independent acceleration measurement", *2009 Asia Communications and Photonics conference and Exhibition*, Shanghai, pp. 1-6.

Zhou, W.J., Dong, X.Y., Ni, K., Chan, C.C. and Shum, P. (2009b), "Temperature-insensitive accelerometer based on a strain-chirped FBG", *Sensors and Actuators A: Physical*, Vol. 157 No. 1, pp. 15-18.

Zhou, W.J., Dong, X.Y., Shen, C.Y., Zhao, C.L., Chan, C.C. and Shum, P. (2010), "temperature-independent vibration sensor with a fiber Bragg grating", *Microwave and Optical Technology Letters*, Vol. 52 No. 10, pp. 2282-2285.

Zhu, J., Wang, J., Gan, P., Hu, Z.L. and Hu, Y.M. (2017), "Design and analysis of a novel dual FBG accelerometer based on lantern shape metallic shells", *IEEE SENSORS Journal*, Vol. 17 No. 16, pp. 5130-5135.

Corresponding author

Li Xiong can be contacted at: xiongli681112@wust.edu.cn