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Investigation of low frequency fibre Bragg grating accelerometer based on thermoplastic cantilever beam

Z M Hafizi^{1,2} and E Vorathin^{2,*}

¹Automotive Engineering Centre (AEC), Universiti Malaysia Pahang (UMP), 26600 Pekan, Pahang, Malaysia

²Advanced Structural Integrity and Vibration Research (ASIVR), Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang (UMP), 26600 Pekan, Pahang, Malaysia

*Corresponding author's email: vora.91.11@gmail.com

Abstract. Vibration measurement technique is very important in structural integrity monitoring. Various fibre Bragg grating (FBG) based accelerometers have been developed for vibration measurement. However, most of the researchers focused on high frequency monitoring and only few reported works are based on low frequency measurement. Therefore, this paper presented a low frequency FBG accelerometer based on Polyphenylene Ether (PPE) thermoplastic cantilever beam. The proposed FBG accelerometer was attached to a shaker and vibration signals were given with variations in frequency and acceleration. As a result, the FBG accelerometer has a sensitivity of 110 pm/g and natural frequency of 9 Hz. The proposed accelerometer capable to detect low frequency of 2 Hz at 0.04 g which is suitable for utilisation in seismic monitoring of earthquake.

Keywords: Fibre Bragg Grating (FBG); Accelerometer; Thermoplastic Cantilever Beam.

1. Introduction

Structural integrity based on vibration measurement technique has been a critical concern in various engineering applications such as oil and gas, railway and earthquake [1, 3]. Therefore, accelerometer has been an essential tool to monitor the vibration signals. Over the years, various sensors have been utilised to develop the accelerometer such as capacitive, piezoelectric fibre optic sensor [2]. Of all sensors, fibre optic sensor based on fibre Bragg grating (FBG) shows great advantages in terms of electrical isolation, immune to electromagnetic and radio frequency interference [4, 5].

Au et al. [3] bonded an FBG on an isosceles triangular cantilever beam. The cantilever beam has the dimension of 32 mm×0.25 mm for length×thickness. The tip of the cantilever beam was attached with a mass of 29.8 grams. As a result, a sensitivity of 21.6 pm/g was obtained across the range of 25 Hz to 150 Hz. Liu et al. [6] developed a copper alloy diaphragm based FBG accelerometer with the diameter of 24 mm. The centre of the diaphragm was attached with a mass of 20 grams. The proposed accelerometer obtained the sensitivity of 36.6 pm/g across the range of 10 Hz to 200 Hz. Compliant cylinder based FBG accelerometer proposed by Zhang et al. [7] obtained a sensitivity of 42.7 pm/g across the range of 30 Hz to 300 Hz. Combination of two cantilever beams with diaphragm FBG accelerometer proposed by Weng et al. [2] obtained the sensitivity of 100 pm/g across the range of 10 Hz to 120 Hz.



However, the aforementioned works reported on a minimum detectable frequency of only 10 Hz. Only few researchers [8-10] have reported on low frequency FBG accelerometer. Low frequency detection is very crucial especially in earthquake monitoring which has the usual frequency range from 0.01 Hz to 50 Hz [1]. Zhang et al. [8] proposed a double-semicircle cantilever beam FBG accelerometer with minimum detectable frequency of 5 Hz at the sensitivity of 1296 pm/g. Bending of spring plates method proposed by Liu et al. [10] capable to capture low frequency of 0.7 Hz. However, both of the proposed methods utilised complex structure. The used of distributed Bragg reflector fibre laser proposed by Zhang et al. [9] capable to detect low frequency of 1 Hz. However, the used of fibre laser is relatively expensive as compared to conventional FBG.

In this paper, a low frequency FBG accelerometer based on Polyphenylene Ether (PPE) thermoplastic cantilever beam has been proposed. The proposed accelerometer capable to capture low frequency of 2 Hz at 0.04 g. The sensitivity of the accelerometer was obtained at 110 pm/g with natural frequency of 9 Hz. Therefore, this paper has successfully presented a high sensitivity FBG accelerometer for low frequency measurement.

2. Design

The proposed FBG accelerometer consists of only three parts which are C-shaped beam for the support base, a “dog bone” shaped PPE cantilever beam and a mass. Figure 1 shows the design and interrogation system of the proposed accelerometer.

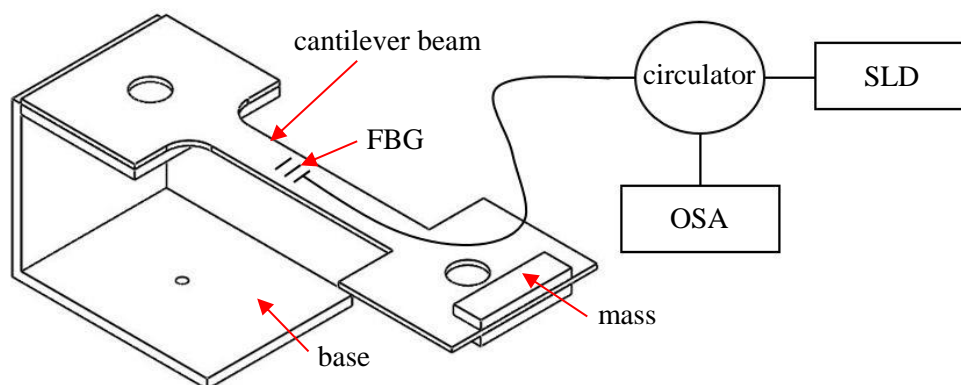


Figure 1. Design and interrogation system of the FBG accelerometer.

The base of the accelerometer was 3D printed made from Polylactic Acid (PLA) material with a height of 30 mm. The PPE cantilever beam has a total length of 95 mm and width at the mid-section of 8 mm. The tip of the cantilever beam was attached with two masses that have the total weight of 3.6 grams. A standard silica glass uniform grating FBG was bonded at the middle of the cantilever beam. A Superluminescent Diode (SLD) light was used to illuminate the FBG via the optical circulator. The reflected spectrum from the FBG was read by the optical spectrum analyser (OSA). The OSA has the wavelength resolution and sample rate of 1 pm and 5000 Hz. At the room temperature of 26.2 °C, the centre wavelength of the FBG was recorded at 1536.5129 nm. Under constant temperature, the centre wavelength change ($\Delta\lambda_B$) of the FBG can be expressed as [8]:

$$\Delta\lambda_B = \lambda_B(1 - p_e)\varepsilon \quad (1)$$

where λ_B is the initial centre wavelength, p_e is the effective elastic-optic coefficient and ε is the axial strain that act on the fibre.

3. Experimental procedures and results

Three experimentations have been carried out in order to assess the characteristics of the proposed accelerometer. The experimental setup was as shown in Figure 2. The FBG accelerometer was attached

to a vibration shaker manufactured by the Data Physics Corporation model V4. A DASyLab software with generator function module was used to excite the vibration of the shaker with sinusoidal wave driven at an amplitude of 5 V. A conventional electrical accelerometer manufactured by the PCB Piezotronics was used to monitor the acceleration of the shaker. The accelerometer has a sensitivity of 10 mV/g and measurement range of -5 g to 5 g where $1\text{ g} = 9.81\text{ m/s}^2$. The sampling rate of the electrical accelerometer was set to 5000 Hz which is the same as the OSA.

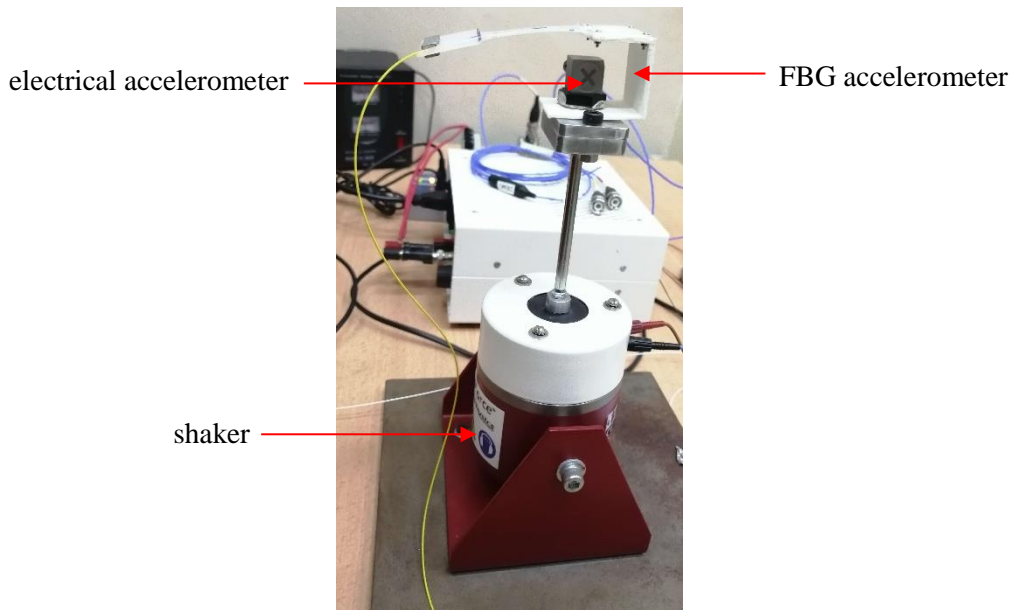


Figure 2. Experimental setup.

3.1 Natural frequency

In order to evaluate the natural frequency of the FBG accelerometer, the acceleration of the shaker was fixed at 0.1 g and the frequency was varied from 5 Hz to 15 Hz. Figure 3 shows the frequency response of the FBG accelerometer.

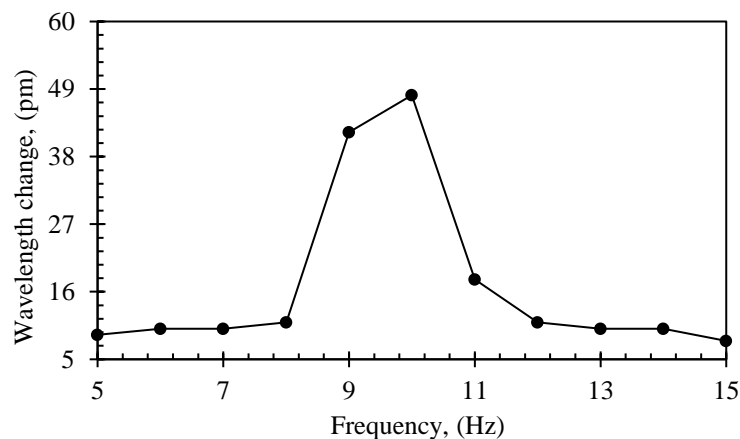


Figure 3. Frequency response of the FBG accelerometer.

By monitoring the wavelength change, a sudden increased in wavelength change was observed at the frequency of more than 8 Hz. The wavelength change at the frequency of 9 Hz and 10 Hz was recorded at 42 pm and 48 pm, respectively. The wavelength change at both the frequencies was four times much

higher than the wavelength change from 5 Hz to 8 Hz. This is because the accelerometer will vibrate in a much larger amplitude under resonant frequency. Therefore, resulted in much larger wavelength change. From the result, the operating frequency of the proposed accelerometer was below 8 Hz. Meanwhile, the natural frequency was determined at about 9 Hz.

3.2 Sensitivity

The sensitivity of the proposed accelerometer can be determined at the flat response range from 5 Hz to 8 Hz. Here, the frequency was fixed at 5 Hz and the acceleration was varied from 0.02 g to 0.1 g with a step of 0.02 g. Figure 4 shows the sensitivity of the FBG accelerometer.

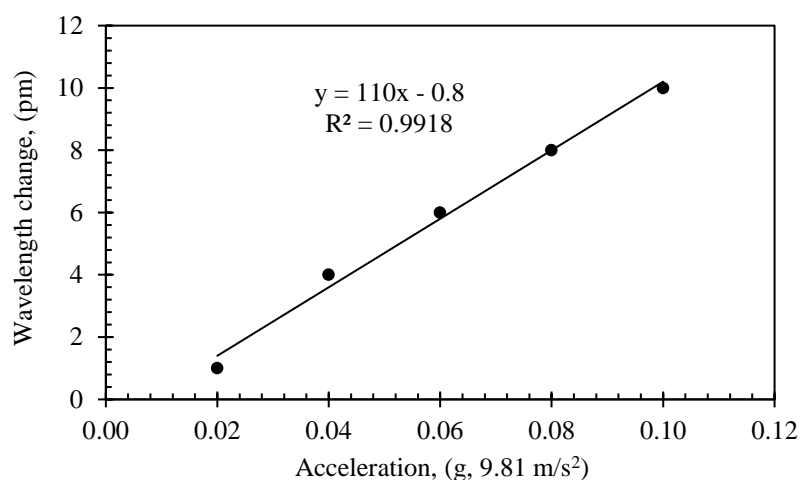


Figure 4. Sensitivity of the FBG accelerometer.

At the initial of 0.02 g, the FBG accelerometer recorded a wavelength change of 1 pm. The wavelength change increased to 10 pm at the maximum of 0.1 g. By determining the slope of wavelength change against acceleration, the sensitivity of the accelerometer was obtained at 110 pm/g. The obtained sensitivity at 110 pm/g was much higher as compared to the previous reported work as in [3, 6, 7].

3.3 Vibration signals

The vibration signals captured by the proposed FBG accelerometer was compared with the electrical accelerometer. Here, the minimum frequency was determined by varying the frequency and acceleration at 1 Hz and 0.01 g until the FBG accelerometer capable to capture the signal. It was observed that the proposed accelerometer capable to capture the lowest frequency signal of 2 Hz at the acceleration of 0.04 g as shown in Figure 5 (a). The signals captured by the FBG accelerometer was an unfiltered signal. On the other hand, the signals captured by the electrical accelerometer was Butterworth filtered with filter order 2 and limit frequency of 10 Hz. The frequency captured at 2 Hz was much lower as compared to the work by Zhang et al [8]. The capability of the proposed accelerometer in capturing low frequency vibration making it suitable for seismic measurement of earthquake. Figure 5 (b) shows the vibration signals at 5 Hz and 0.1 g. The frequency (f) captured by the signals can be calculated as [11]:

$$f = \frac{1}{T} \quad (2)$$

where T is the period of time in second for one complete oscillation. From Figure 5 (a) and Figure 5 (b), clearly seen that the frequency signals captured by the FBG accelerometer at 2 Hz and 5.07 Hz was closed to the electrical accelerometer at 1.93 Hz and 5.09 Hz.

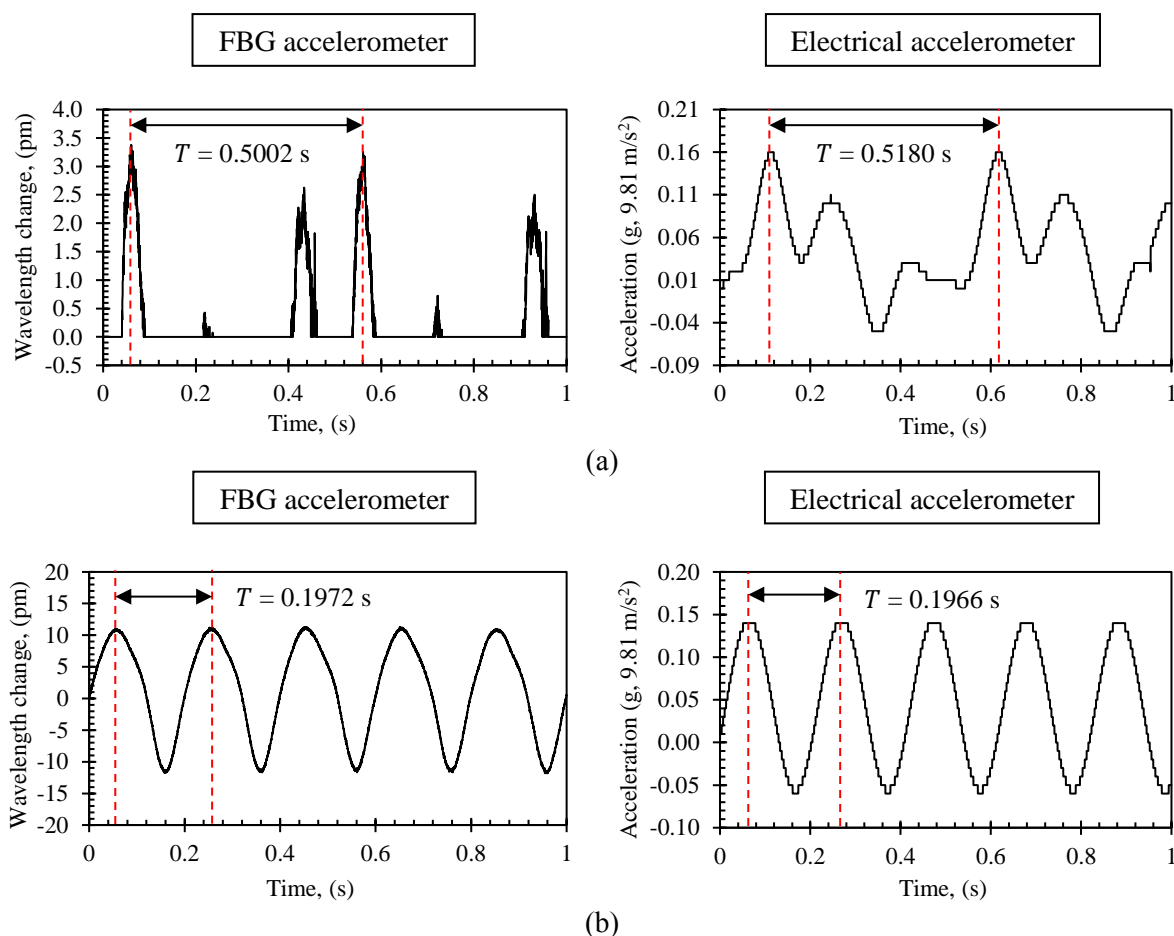


Figure 5. Vibration signals at (a) 2 Hz, 0.04 g and (b) 5 Hz, 0.1 g.

4. Conclusion

This paper has successfully presented a low frequency FBG accelerometer based on PPE thermoplastic cantilever beam. A series of experimentations have been carried out to determine the characteristics of the proposed accelerometer. From natural frequency test, the proposed accelerometer has a first mode natural frequency at 9 Hz. Therefore, the operating range of the FBG accelerometer was below 8 Hz with the sensitivity at 110 pm/g. Comparison of the vibration signals captured by the FBG accelerometers was similar to the electrical accelerometer. The lowest frequency capable to be captured by the FBG accelerometer was at 2 Hz and 0.04 g.

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