Improving frequencies range measurement of vibration sensor based on Fiber Bragg Grating (FBG)

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Abstract. This research aimed to develop a vibration sensor based on Fiber Bragg Grating (FBG). The design was mainly done by attaching FBG at the cantilever. The free-end of the cantilever was tied to a vibration source in order to increase the measurement range of vibration frequencies. The results indicated that the developed sensor was capable of detecting wide range of frequencies (i.e. 10 - 1700 Hz). The results also showed both good stability and repeatability. The measured frequency range was 566 times greater than the range obtained from the previous works.

1. Introduction
There have been many uses of FBG in optical sensor applications, such as vibration sensors [1, 2], temperature [3], load [4], strain [3, 4], and liquid level [5 – 7]. The focus this study is using FGB as a vibration sensor. The working principles of FGB as a vibration sensor are either intensity, phase or wavelength modulation [1, 2]. Generally, FGB as a vibration sensor can work at low frequencies, i.e. less than 100 Hz [1, 2, 8 – 10] and using the wavelength modulation technique. This technique utilizes the changes in grating period due to external stimuli resulting wavelength shift Bragg. Therefore, modulation requires a broadband light source and optical spectrum analyzer (OSA) to display the output signal. In this work, we use the intensity modulation based on the light source that has a spectral width that is narrower than the reflection spectrum of FBG. In this case, we use a laser diode as a light source. Fig. 1 shows the working principle of FBG where a dynamic strain on FBG affects the reflected intensity of laser diode before (a) and after (b) vibration.

If the polychromatic or a broadband light source propagate on FBG then there will be a spectrum with a specific wavelength is reflected. When the FBG is not vibrated the laser source spectrum will be fully reflected. If FBG was vibrated there will be the changes in the intensity of the reflected laser source [11]. FBG shows a shift response to the changes in light reflectance on FBG at certain wavelengths. In this system, a laser diode which has a narrow spectrum of wavelength was set to approach Bragg wavelength. Mathematical description of the FBG principle can be written as follows:

\[ \lambda_B = 2n_{eff} A \]  

(1)
where $\lambda_B$ is Bragg wavelength, $n_{eff}$ is effective refractive index and $\Lambda$ is period of gratings of FBG[8,11-13]. If the grating period FBG is changed due to dynamic strain from outside, the Bragg wavelength also changes. Fig. 2 shows the change in the intensity of the laser diode which is reflected by the dynamic strain of the FBG due to vibration [3, 13].

In this work, the technique used is based on the changes intensity of the reflection by FBG. The aim of this research is to increase the measurement range of the FBG sensor more than 1000 Hz.

2. Methodology
We use a cantilever with a dimension of $60 \times 3 \times 0.5$ mm as a vibration source for FBG. Figure 3 shows the bronze cantilever used in this study. The resonance frequency of the cantilever can be expressed using equation [10, 13, 14]:

$$f = \frac{1}{2\sqrt{\frac{3EI}{L^3M}}}$$

(2)

where $f$ is resonance frequency, $E$ is the Young modulus of bronze, $I$ is a moment of inertia, $L$ is the length of cantilever, and $M$ is an effective mass. We found that the cantilever has a resonance frequency of 200 Hz. Moment of inertia, can be expressed using the equation:

$$I = \frac{bd^3}{12}$$

(3)
Using equation (3), we found that the cantilever has moment of inertia $3.13 \times 10^{-14} \text{ m}^4$. On the middle of the cantilever, a polyamide FBG with center wavelength $\lambda_B = 1607.7 \text{ nm}$ was attached. This FBG has a uniform gratings structure with a length of 1 mm. It also has the bandwidth of 1.6 nm and a reflectance $> 50\%$.

Figure 4 is the experimental set-up of the FBG based vibration sensor. The light source was a tunable laser diode (TSL-510) with a wavelength range of 1560-1680 nm. The laser was propagated through optical circulator toward the FBG attached on the cantilever. The free-end of the cantilever was then tied to a vibration source (a speaker device) with a frequency controlled by a signal generator. The frequency was tuned in 10 - 2000 Hz range. At a given vibration with a specific frequency input, the intensity-response of the laser source that reflected by FBG was captured by a high-speed photodetector (HSPD). Data acquired from the photodetector was then processed by LabVIEW software. Representation data in frequency domain were obtained using Fast Fourier Transform (FFT).

To increase the sensor sensitivity, we set the center of Bragg wavelength at 1604.738 nm and the laser source at 1604.000 nm using an optical spectrum analyzer. Figure 5 shows the Bragg wavelength and laser source that were set in this work.

![Figure 3. The dimension of cantilever [13]](image)

![Figure 4. Experimental on set-up of the FBG based vibration sensor. Inset: How the cantilever tied to a vibration source](image)
3. Result and discussion

Intensity responses of laser light due to the vibration of cantilever were captured by a photodetector and processed using a LabVIEW to represent in the time domain. These data were then analyzed using FFT to represent in the frequency domain. Figure 6(a) is one of the raw data from vibration recorded in the time domain for the input frequency of 200 Hz. The raw data was then analyzed directly using FFT to obtain the amplitude and the output frequency. Figure 6(b) is the representation of vibration with a frequency of 200 Hz after analyzed using FFT. Note that there is no shift in the output frequency.

To show the linearity between the frequency of the input vibration and the output frequency, we scanned all the possible frequencies that can be produced by the signal generator. Figure 7 shows the output frequency of 500 and 1000 Hz for the input frequencies at the same values. There was no different in the frequencies between an input signal and output signal. If the input signal increases, the output also increases with the equal value.

Based on the dimension and the type of cantilever’s material, we can determine the resonance frequency of cantilever with the equation (2) i.e. 200 Hz. In this experiment, we generated the input frequency of 10 - 2000 Hz and we got the maximum amplitude of 1.5 cm for the resonance frequency of 200 Hz, as shown in figure 8. It is obvious that the maximum amplitude was obtained when the
frequency of the input signal was equal with the resonance frequency. This indicated that resonance frequency can make the maximum amplitude in vibration of cantilever. This experiment can detect an amplitude of vibration of frequency up to 1700 Hz. The maximum frequency of the input signal is 1700 Hz to produce amplitude that can be measured by system. When the frequency of the input signal was higher than 1700 Hz, the amplitude of vibration was zero.

We also examined the sensor stability. The stability test showed that the sensor can work properly. There was no interference which could affect the output signal. Figure 9 shows the stability of the sensor in terms of the output frequency. The sensor can operate smoothly with frequency up to 1700 Hz. From the lowest frequency until 1700 Hz, stability of sensor still capture the same value of the output frequency.

**Figure 7.** Representation data with frequency 500 Hz (a) and 1000 Hz (b)

**Figure 8.** Relationship amplitude and input frequencies that can be produced until 1800 Hz.
Figure 9. The stability of the sensor for the output frequency produced.

4. Conclusion
Development of FBG based vibration sensor has been done. The sensor was capable of detecting the vibration frequencies at the range of 10 - 1700 Hz with no shift. The results also showed both good stability and repeatability. The measured frequency range was 566 times greater than the range obtained from the previous works.

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