Fiber Bragg grating seismic sensor using inverted spring-mass system

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ABSTRACT

A simple seismic vibration sensor is designed using fiber Bragg grating (FBG) with aid of an inverted spring-mass system. An inertial mass is attached to the spring enables to oscillate in axial direction only when it is subjected to seismic vibration (P-wave). The spring mass system facilitates free motion only in one direction that is parallel to the base. An interrogation system is developed using Single mode-Multimode- Single mode (SMS) configuration to monitor the Bragg wavelength shift of FBG into its equivalent optical intensity modulation corresponding to the seismic vibration. The experimental results show that proposed sensor is capable of measuring the vibrations of frequency over the range of 2-20Hz. Further, it is evident from the results that the sensor is highly sensitive at 7.5Hz represents the resonance frequency of the designed sensor system. The range of the frequency measurement can be optimized by changing the spring parameters or overhead weight (mass) and also the position of the FBG attached between the spring and support. Thus designed sensor head enables low-cost measurement and fast response in real time applications.

Keywords: Fiber Bragg grating, Inverted spring-mass, Seismic sensor, Interrogation, Vibrator, SMS structure, (P-wave).

1. INTRODUCTION

Since four decades fiber optic sensors have been revolutionize for sensing of various parameters like strain, temperature, displacement, vibration and pressure in the fields of industrial and R&D applications [1-3]. In many applications a fixed reference vibration sensors are not available, therefore the spring-mass system is used, which exhibits an oscillatory motion act as reference to the strain measuring transducer [4]. In general, seismic vibration measurement sensors are designed based on either mechanical or electrical design [5]. Though, mechanical sensors are robust, they are designed with corrosive materials suffered by an aging effect and slow response when compare to other techniques. The electrical seismic sensors are not suitable for the real time applications due to their electrical conductivity, make them inappropriate for electromagnetic interference (EMI) environments. Commercially available sensors work based on the variation of resistance, capacitance or inductance. The materials used to make these sensors are temperature sensitive and corrosive. In order to overcome these problems different fiber optic seismic sensors have been treated as best replacement over conventional sensors due to their advantages like immune to EMI, small size, temperature insensitive (compensation), easy to install, remote sensing capability and real time monitoring. In comparison with intensity and wavelength modulated sensors, the fiber optic Interferometric sensors are not suitable for real time applications due to their critical alignment and analysis, highly sensitive to temperature and also not suitable to lower frequency range [4, 6-7]. In general all the seismic sensors detect s-wave vibration. To measure the p-wave vibration an inverted spring mass system is designed along with FBG.

This paper reports a design of FBG seismic vibration sensor based on the inverted spring-mass system to sense the p-wave seismic vibration that can be used for real time and remote monitoring applications. A linear edge filter is designed using SMS configuration to interrogate the FBG response corresponds to variation in seismic vibrations. A method is discussed to discriminate the temperature effect on seismic vibration sensing.

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2. THEORY

In general seismic vibrations are the dynamic deformations of the earth or structure needs real time monitoring and control or record from the remote place. Fiber optic sensors are well suitable for such kind of applications due to their inherent advantages. The sensor is designed using inverted spring holding the inertial mass arranged such a way that to produce vibrations in axial direction to that of optical fiber. The axial seismic vibration of the body is measured by measuring the axial strain produced by the FBG with respect to oscillatory motion of the spring-mass system. The frequency response of the sensor system is depending on two factors. The first dominant and very important factor that is natural frequency f_k of the spring-mass system which can be obtained by using the following equation [8-9]

$$f_k = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

Where k is the spring constant and m is the mass suspend by the spring.

The second factor is the intrinsic resonance frequency of the optical fiber and is described as [10]

$$f_o = \frac{1}{2\pi}\sqrt{\frac{2.k_f}{m_t}} \tag{2}$$

Where k_f is the spring constant of the quartz fiber depends on the area and length of the optical fiber used, m_t is the total inert mass (spring and inertial mass) of the sensing system.

2.1 Principle of FBG

Fiber Bragg grating is characterized by a periodic perturbation of the core refractive index along a given length of an optical fiber. When FBG is illuminated with broad band light, due to the coupling between incident and counter propagating optical modes, the specific narrowband wavelength light will be reflected which is called Bragg wavelength λ_B can be expressed as [1]

$$\lambda_B = 2\eta_{eff}\,\Lambda \tag{3}$$

Where η_{eff} the effective refractive index of the fiber core and Λ is the grating period. Any changes in fiber properties, such as strain or temperature which varies the effective refractive index or grating period will change the Bragg resonance wavelength.

The shift in Bragg wavelength corresponds to applied strain and temperature can be expressed as [1]

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial\eta_{eff}}{\partial l} + \eta_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial\eta_{eff}}{\partial T} + \eta_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{4}$$

The first term in equation (4) denotes the strain effect on an optical fiber. This corresponds to change in grating period and strain-optic induced change in the refractive index. The strain effect term can be expressed as

$$\Delta\lambda_B = \lambda_B(1 - P_e)\varepsilon \tag{5}$$

Where P_e is the effective photo-elastic coefficient of the fiber can be approximated as P_e = 0.22 [1].The second term in equation (4) represents the temperature effect on an optical fiber. A shift in Bragg wavelength due to thermal expansion, changes the grating pitch and the index of refraction. This Bragg wavelength shift for a temperature change ΔT can be written as

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \xi_n)\Delta T \tag{6}$$

Where $\alpha_\Lambda = \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial T}$ is the thermal expansion coefficient of the optical fiber. The quantity $\xi_n = \frac{1}{\eta_{eff}}\frac{\partial \eta_{eff}}{\partial T}$ represents the thermo-optic coefficient. Thus from equations (5) and (6) the fractional change in Bragg wavelength associated with the change in strain and temperature can be expressed as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-P_e)\varepsilon + (\alpha_\Lambda + \xi_n)\Delta T \tag{7}$$

Accordingly, it is evident from equation (7) that, in sensing applications where only one perturbation is of interest, therefore the discrimination of strain and temperature emerge as significant.

2.2 Discrimination of temperature and seismic vibration (strain)

From the analysis, it indicates that both changes in vibration (strain) and temperature can induce the changes in the Bragg wavelength. In general, the common method to discern them is using another reference FBG (FBG2), being thermal contact with the sensing FBG (FBG1), but is shielded from the applied vibration. When the vibration is applied to the FBG sensor or when there is an ambient temperature change, the effective refractive index and the grating pitch will change, and therefore the resonance wavelengths will shift. The shifts of resonance wavelengths for FBG1 and FBG2 can be expressed as [11, 12]

$$\Delta\lambda_{B1} = J_{S1}\Delta S + J_{T1}\Delta T \quad \text{and} \quad \Delta\lambda_{B2} = J_{S2}\Delta S + J_{T2}\Delta T \tag{8}$$

Where J_{S1}, J_{T1}, J_{S2} and J_{T2} are strain and temperature sensitivity coefficients of FBG1 and FBG2 respectively. From equation (8), when strain and temperature changes, the strain can be obtained on the basis of subtracting the Bragg wavelength shift induced by the reference FBG(FBG2) from the total wavelength shift induced by the sensing FBG (FBG1). To realize the simultaneous measurement of strain and temperature, the Bragg wavelength shift of two resonant peaks of corresponding FBGs need to be measured simultaneously. In this way, discrimination between strain and temperature can be achieved by the following matrix equation

$$\begin{bmatrix} \Delta S \\ \Delta T \end{bmatrix} = \frac{1}{\psi}\begin{bmatrix} J_{T2} & -J_{T1} \\ -J_{S2} & J_{S1} \end{bmatrix}\begin{bmatrix} \Delta\lambda_{B1} \\ \Delta\lambda_{B2} \end{bmatrix} \tag{9}$$

Where $\psi = J_{S1}J_{T2} - J_{S2}J_{T1}$, strain and temperature sensitivity coefficients can be determined experimentally by measuring separately the shift of Bragg wavelengths of the FBGs.

3. INTERROGATION OF THE FBG USING SMS STRUCTURE

In general FBG gives the wavelength shift corresponds to change in strain/vibration or temperature. Particularly, for real time monitoring of seismic vibration fast and high resolution interrogation system is required. Aiming to attribute this simple, high speed and cost effective integration scheme using single mode-multimode-single mode (SMS) configuration designed and experimentally demonstrated. The induction of fiber edge filter using SMS configuration to match with the Bragg wavelength of FBG can be optimized by changing the length of the multimode fiber [13, 14]. The design of SMS fiber structure encompasses the splicing of a step-index multimode fiber (MMF) between two standard single mode fibers (SMF-28e). The schematic of the SMS fiber structure is shown in figure 1. The fabrication principle of linear edge filter can be described as follows: the light field propagating along the input SMF enters into the MMF section and excites a number of guided modes in the MMF. Interference between the different modes occurs while the light field propagates through the MMF section. By choosing a suitable length for the MMF section, the light coupled into the output SMF could be a wavelength dependent manner due to the interference.

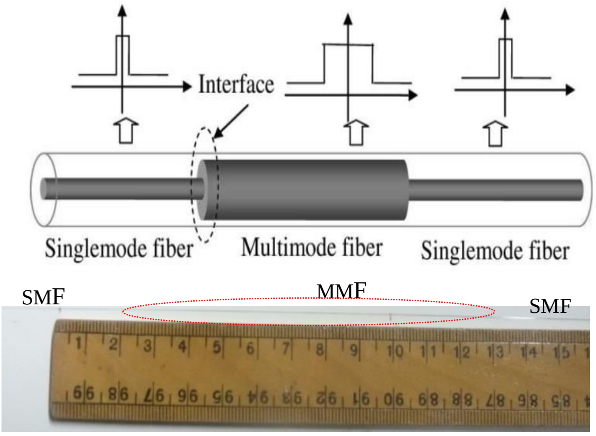

Figure 1.Schematic configuration of the single-mode–multimode–single-mode fiber structure.

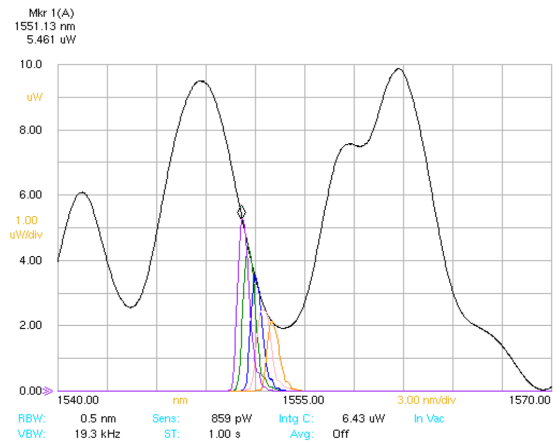

Figure 2.OSA spectrum of the designed SMS configuration for Interrogation.

The length of the MMF section determines the operating wavelength range of the filter. The transmission spectrum of the designed SMS structure for optimized length of 10 cm is shown in figure 2. This band-pass response exhibits as a two linear edge filter response on the either side of the center wavelength at 1553.75nm. Consequently this device can be used as an edge filter over a selected wavelength range. Therefore the negative slope ranges 1548-1553 nm shown in figure 2 is used to interrogate the FBG (Bragg wavelength at 1551nm) response corresponds to seismic vibration.

Figure 2 shows the optical intensity modulation related to the shift in Bragg wavelength of FBG corresponds to seismic vibration. A simple photo-detector along with a transimpedance amplifier circuit shown in figure 3 is used to convert the detected optical intensity information into readable voltage signal.

The figure 4 illustrates the FBG response corresponds to seismic vibration recorded using OSA, and also the equivalent optical intensity modulation obtained by using SMS linear edge filter which is detected by the photo-detector. From the above results it is observed that the experimental results obtained using both OSA and designed detection system of the interrogator are well matched with a linearity coefficient of 99%.

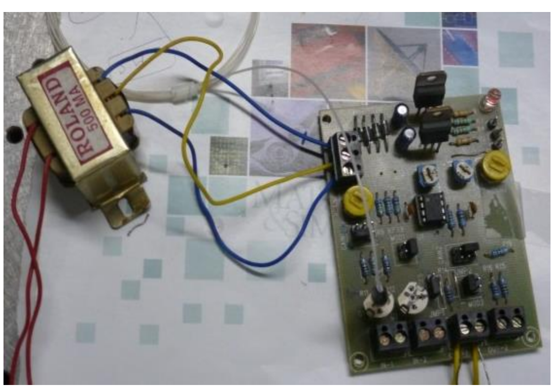

Figure 3.Photograph of the designed transimpedance amplifier circuit along with photo-detector.

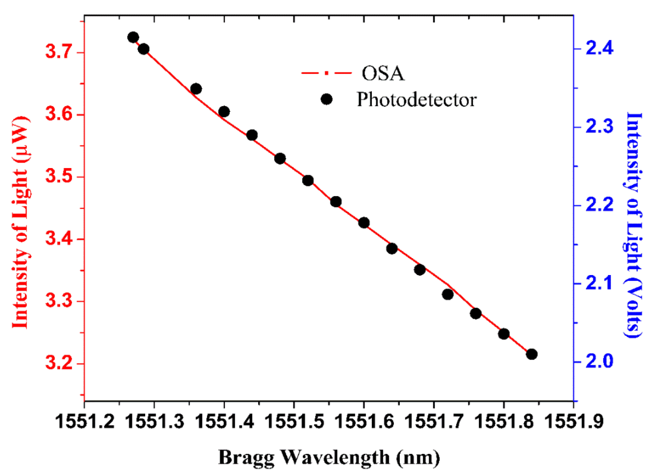

Figure 4.The interrogation results of the FBG response using SMS structure.

4. EXPERIMENT

The schematic experimental setup of the FBG seismic vibration sensor is shown in figure 5(a).

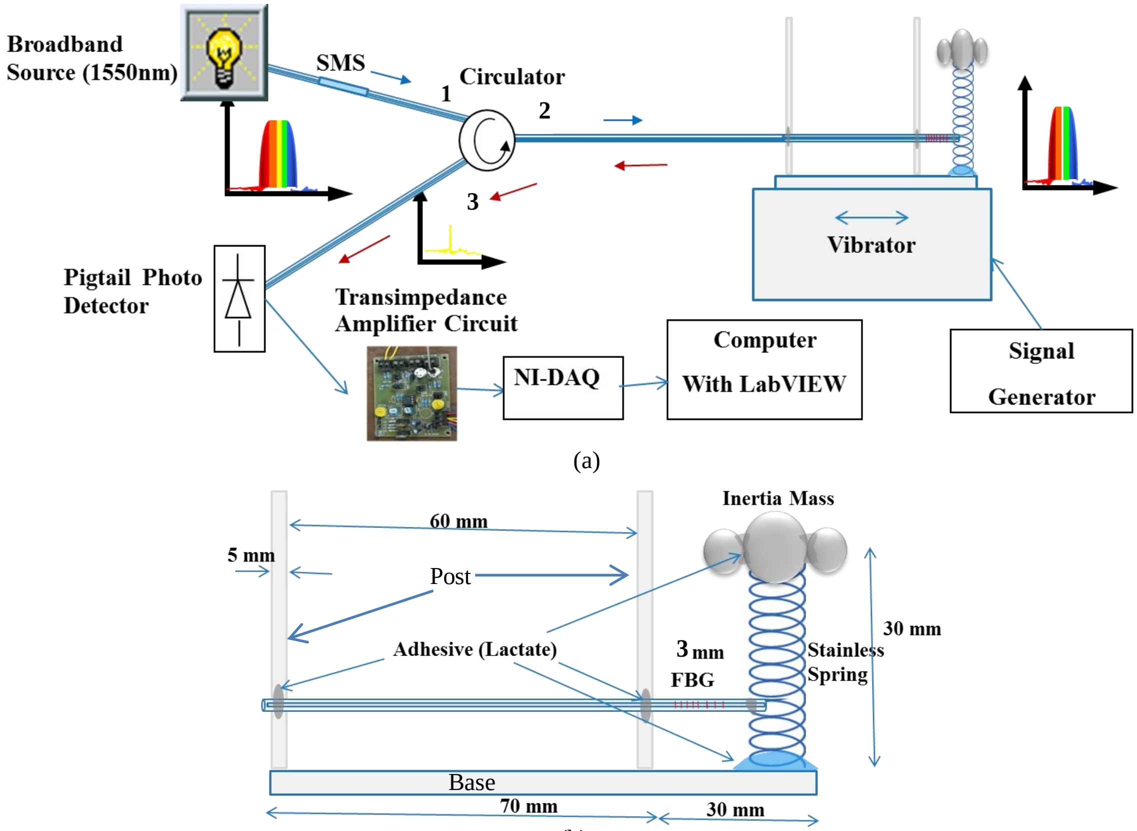

Figure 5. (a) Schematic experimental setup and (b) designed sensor head for seismic vibration sensing.

Dimensions of the sensor head and FBG attached to the spring-mass system is shown in figure 5(b). The light from the broadband source (Thorlabs-S51005S) having peak wavelength at 1540nm is coupled to SMS interrogator then transmitted to port1 of the circulator. The light from the port 1 is directed towards port 2 and transmitted to FBG. The reflected Bragg wavelength of the FBG is directed towards port 3, which is incident onto the photo-detector (DPIN-23113). A transimpedance amplifier circuit is designed to convert the detected light into its equivalent voltage signal. This signal is collected by the NI-DAQ and then monitored and processed by LabVIEW in a PC for the analysis of seismic vibration. A synthesized signal generator (HM8130) is used to vibrate the designed seismic vibrator at different frequencies with variable amplitude.

The FBG of length 3mm having peak wavelength at 1551nm is used as a sensor. The FBG is fixed between the one of the post and fourth turn of the helical spring (at a height of 9.5mm from the base). The natural frequency of the fiber (SMF28e) of length 21mm glued between the post and the spring mass system is calculated from equation (2) found to be 780Hz. The spring is made of spring steel has spring constant of 0.135 N/mm for its dimensions. An inertial mass of 3gm is glued on the overhead of the spring shown in figure 5(b). Thus the natural frequency of the spring-mass system is calculated from equation (1) found to be 34Hz. From these natural frequencies of the optical fiber and spring-mass system, the sensor is capable to measures the seismic vibration below the 34Hz only. Therefore, the frequency range can be varied by changing the parameters of fiber or spring-mass system. As the spring vibrates corresponding to the vibration of the vibrator produces a strain change in the FBG. Further, the wavelength encoded information corresponds to seismic vibration is converted into equivalent electrical signals.

5. RESULTS AND DISCUSSIONS

To study the response of the sensor, the sensor head is mounted on the seismic vibrator which is controlled by a signal generator. The designed vibrator is calibrated using dual optical fiber vibration sensor for the amplitude measurement [17]. Figure 6 shows the displacement response between the sensor head to the reflecting surface which is attached to the vibrator. At first studied the stability of the seismic sensor that is without applying any vibration. It was found that the signal is high stable, for a period of 27sec as shown figure 7. Experiments were conducted by applying the sinusoidal signal at different frequencies and amplitudes to the vibrator, which produce the vibration in spring-mass system tends to create an axial strain in the FBG causes shift of Bragg wavelength which is recorded in terms of equivalent electrical signal. Figure 8 shows the time domain output signals and corresponding frequency spectrums using FFT technique of the sensor for known applied frequency of 2Hz at the acceleration amplitude of 0.078g.

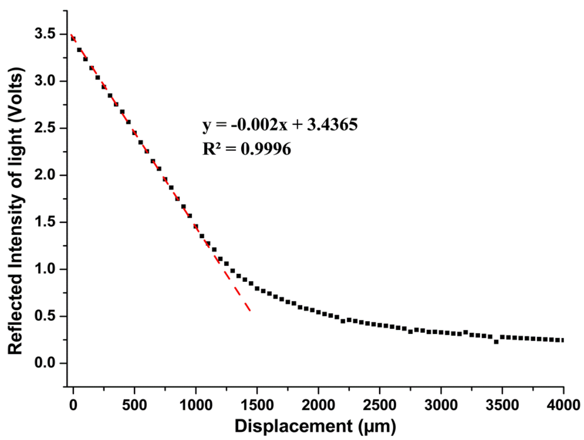

Figure 6.Displacement response of the dual fiber optic sensor for amplitude calibration of the vibrator

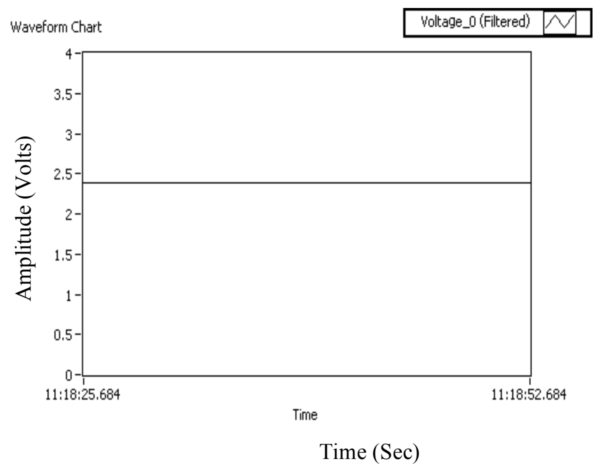

Figure 7.Time domain signal of the FBG seismic sensor without any vibration.

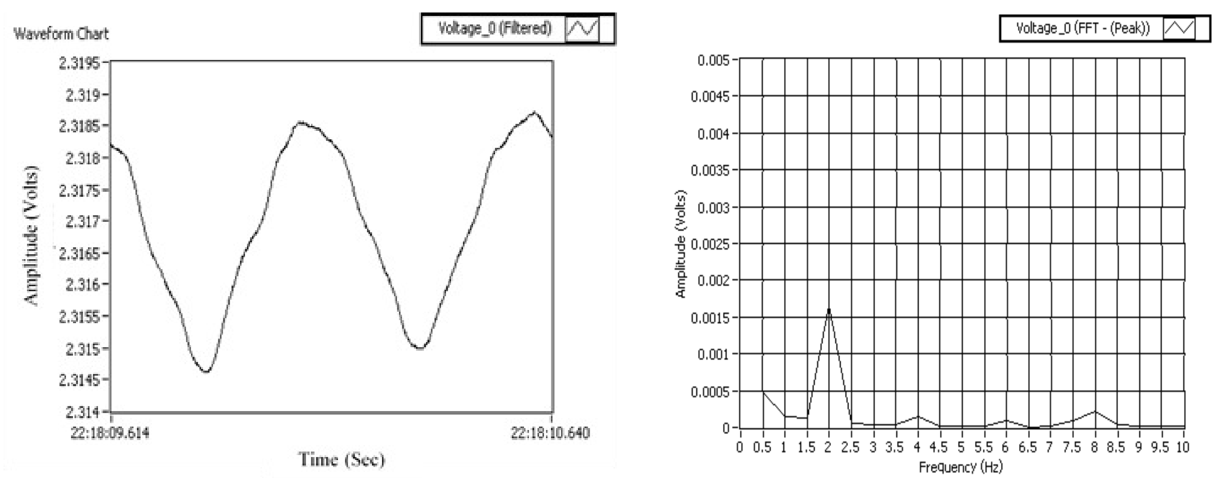

Figure 8.Time domain signal and corresponding FFT spectrum of the FBG seismic sensor system at 2Hz frequency.

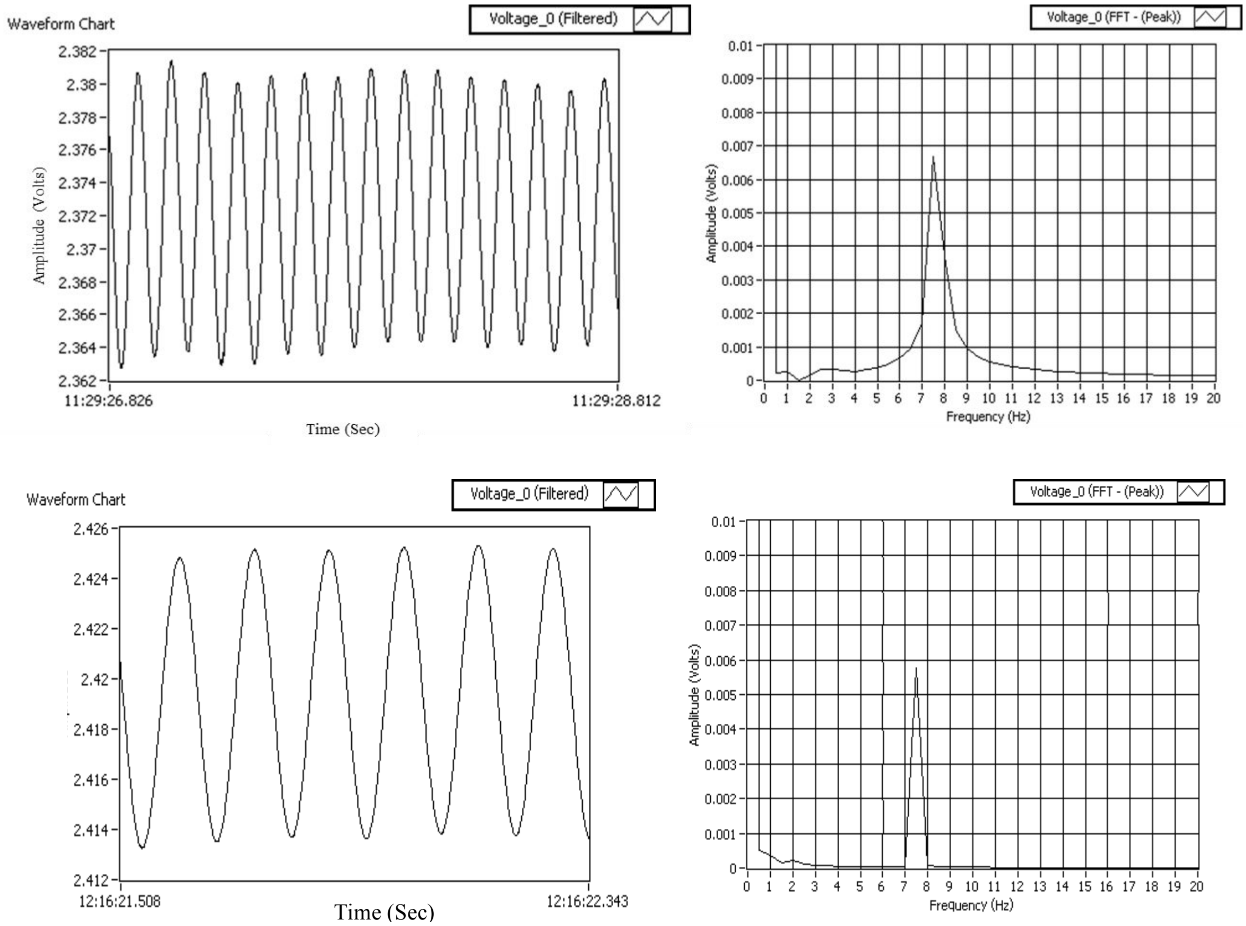

Figure 9.Response of the sensor at constant frequency of 7.5Hz for varying amplitudes of a) 0.0065g and b) 0.0052g.

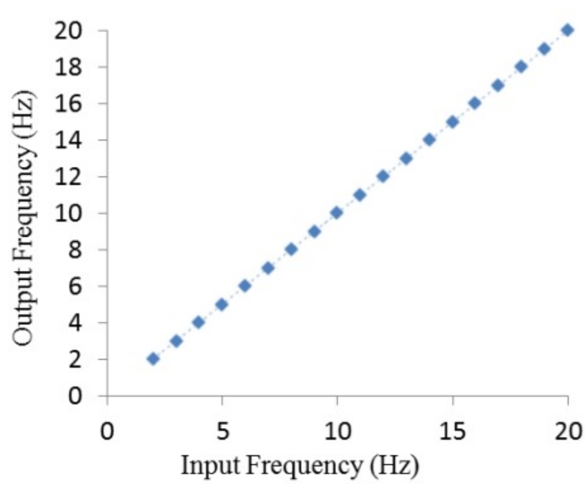

Figure 10.Frequency response of the sensor for known applied frequencies

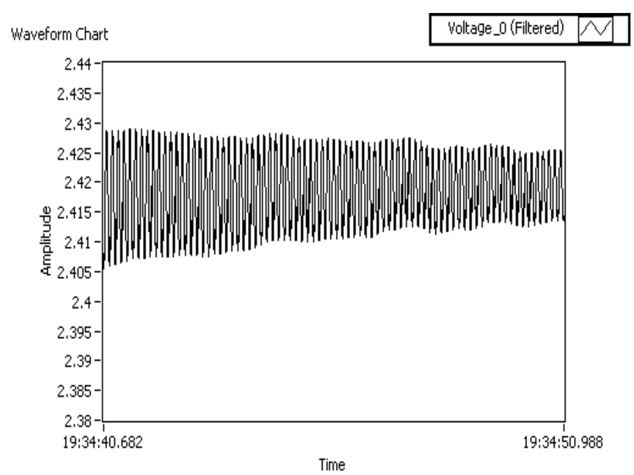

Figure 11.Response of the sensor for the continuous varying amplitude at constant frequency of 7.5Hz.

Figure 10 shows the frequency response of the FBG seismic vibration sensor and found that good matching between the input frequencies applied to the vibrator and the output frequency measured from the designed sensor. It is observed from the results that the sensor is capable to measure the frequencies of range 2-20Hz. Below 2Hz the sensor head that is spring-mass system is not showing any oscillatory motion due to its inertial mass. Above 2Hz the sensor response is good up to 20Hz which is considered as an upper limit of the proposed sensor. Therefore experimental results reveals that the combined system can be used to sense the frequency up to 20Hz only due to the resonance frequency of optical fiber and spring mass system are limited to 780Hz and 34Hz respectively.

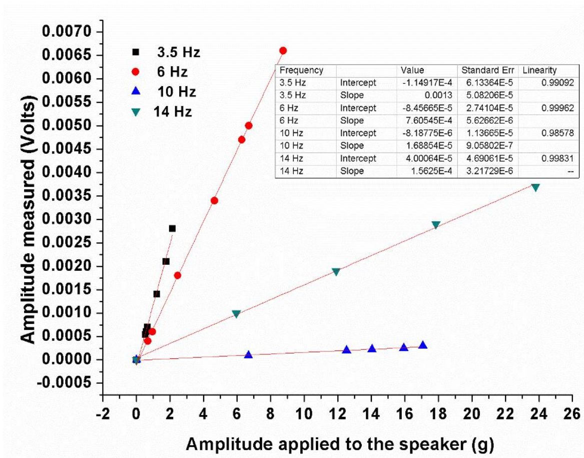

Figure 12.Amplitude response of the sensor at different frequencies.

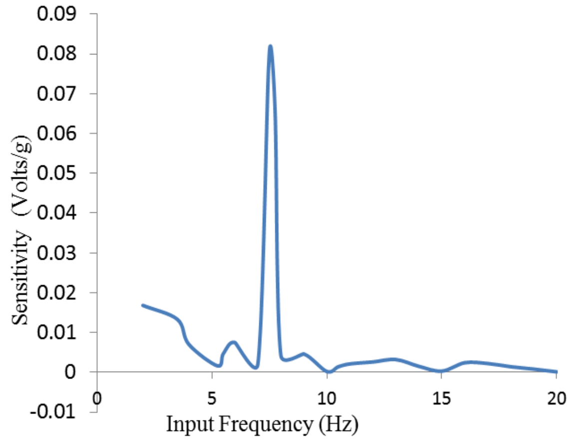

Figure 13.Amplitude sensitivity corresponding to the frequency characteristic curve of the sensor.

The amplitude response of the sensor is also tested by varying the amplitude continuously at constant frequency of 7.5Hz as shown in figure 11. Figure 12 represents the amplitude response at different frequencies and illustrated that there is a linear relationship between the applied and measured amplitude of vibration. The amplitude is varied at constant frequency and measured the amplitude sensitivity at that frequency. The same experiment is repeated at different frequencies and measured the sensitivities, then plotted the characteristic curve between the amplitude sensitivity and frequency as shown in figure 13. It is observed that at 7.5Hz the sensor shows high sensitivity represents the resonance frequency of the sensor system. The resonance frequency and range frequency can be changed by varying the parameters of the optical fiber or spring-mass system and also the position (height from the base) of the FBG glued to the spring.

Since the FBG is sensitive to both strain and temperature, to attain pure vibration measurement the thermal-stain cross sensitivity should be eliminate in practical applications. Therefore equation (9) can be used to determine the simultaneous measurement of vibration and temperature.

6. CONCLUSIONS

An attempt was made to design the FBG seismic vibration sensor using an inverted spring-mass system. The sensor is configured using a vertical spring glued with overhead weight provides damped motion of the spring in axial direction with respect to the seismic vibration (P-wave). An interrogation system is developed using single mode multimode single mode (SMS) structure to monitor the Bragg wavelength shift of FBG in terms optical intensity modulation corresponding to the seismic vibration. Thus it enables low-cost measurement and fast response in real time applications. The experimental results show that the proposed sensor is able to measure the frequency of vibrations over the span of 2-20Hz. It is also evident from the results that the sensor is highly sensitive at 7.5Hz represents the resonance frequency of the designed sensor system. The resonance frequency and the range of the frequencies can be optimized by changing the spring parameters or overhead weight and also the position of the FBG attached between the spring and the post. The discrimination of the temperature from the seismic vibration is also discussed to measure these parameters simultaneously.

5. ACKNOWLEDGEMENTS

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