An etched fiber optic vibration sensor to monitor the simply supported beam

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Abstract

A single mode fiber optic vibration senor is designed and demonstrated to monitor the vibration of a simply supported beam. A rectangular beam (length 30.8 cm, width 2.5cm and thickness 0.5mm) made of spring-steel is arranged as simply supported beam and is made to vibrate periodically. To sense the vibrations a telecommunication fiber is chemically etched such that its diameter reaches 50µm and is glued using an epoxy at the centre of the beam. A broadband light (1550nm) is launched into Fiber Bragg Grating (FBG) through a circulator. The light reflected by the FBG (1540.32nm) is coupled into the centre etched fibre through the circulator and is detected by photodiode connected to a transimpedance amplifier. The electrical signal is logged into the computer through NI-6016 DAQ. The sensor works on transmission power loss due to the mode volume mismatch and flexural strain (field strength) of the fiber due to the bending in the fiber with respect to the bending of the spring-steel beam. The beam is made to vibrate and the corresponding intensity of light is recorded. Fast Fourier transform (FFT) technique is used to measure the frequencies of vibration. The results show that this sensor can sense vibration of low frequency accurately and repeatability is high. The sensor has high linear response to axial displacement of about 0.8 mm with sensitivity of 32mV/10µm strain. This low-cost sensor may find a place in industry to monitor the vibrations of the beam structures and bridges.

Keywords: Optical Fiber, Fiber Bragg Grating, Etched fiber, simply supported beam, vibration sensor, health condition, monitoring.

1. Introduction

Now-a-days the structural beams are used in all branches of engineering, mainly in Civil, Mechanical, Nuclear Power plants etc. Simply supported beams are one of the important structures in real life. The study of dynamic vibration response of a beam and frequency analysis gives enough information about the structural imperfections [1, 2]. Generally, in real time the forces are non-periodic and are suddenly released forces [3]. The conventional structural health monitoring systems do not respond immediately, effected by electromagnetic waves and are corrosive. On the other hand Fiber Optic sensing systems respond immediately, not affected by electromagnetic waves and are non-corrosive. Fiber Optic sensors have been shown to be capable of measuring a variety of parameters including bending with high sensitivity and are stable even at high temperatures [4, 5].

The aim of the present work is to design an inexpensive fiber optic vibration sensor to monitor the dynamic response of a rectangular simply supported beam with symmetric overhang. The sensor works on the principle of intrinsic intensity modulation corresponding to a force applied at the centre of the beam where etched portion of the sensing fiber is attached. The sensors response is studied for the applied and suddenly released forces. The sensor has advantages of simple design, flexible in length, small in size and can be embedded in composite structures.

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2. Theory of Simply supported beam:

A simply supported beam of length '*l*' width '*b*' and thickness '*h*' with symmetric overhang '*m*' is considered . The geometry of the beam is shown in figure 1.

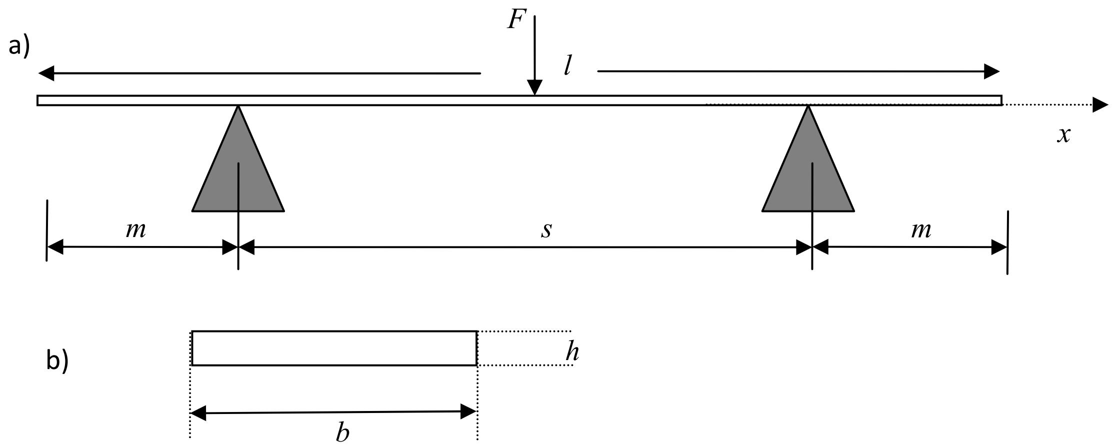

Figure 1. a) Geometry of the simply supported beam b) Cross section of the beam.

The effects of shearing, rotatory deformations are ignored as the cross-sectional dimensions are constant and small in comparison to its length. Here the transverse vibration of the beam is considered as a one degree problem [6-8]. The lateral displacement of the beam along the length for concentrated force or load applied at the centre is expressed as [9]

$$y = \frac{Fx}{12EI}\left(\frac{3l^2}{4} - x^2\right) \qquad \text{for } 0 < x < \frac{l}{2} \qquad (1)$$

$$y = \frac{F}{12EI}\left(x^3 + \frac{9xl^2}{4} - \frac{l^3}{4} - 3lx^2\right) \qquad \text{for } \frac{l}{2} < x < l \qquad (2)$$

The bending of the beam at the centre where the force or load applied is

$$y_{max} = \frac{F}{4Eb}\left(\frac{l}{h}\right)^3 \qquad (3)$$

The free transverse vibration of the simply supported beam corresponding to concentrated load at the centre is expressed as [10]

$$y(x,t) = \sum_{n=1}^{\infty} \frac{2Fl^3}{n^4\pi^4 EI} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi x}{l}\right) \cos\left(w_n t\right) \qquad (4)$$

Where w_n is the natural frequency of the overhang beam and is given by

$$w_n = \left(\frac{2\pi}{s}\right)^2 \sqrt{\frac{EI}{A\rho}} \qquad (5)$$

Where *E, I, ρ and A* are the modulus of elasticity, moment of inertia, density and cross-sectional area of the beam respectively.

When the force is applied at the centre of the beam and it is released suddenly, the vibration of the beam undergoes a damped motion following a near step and giving the overshoot that slowly decays exponentially towards zero of the amplitude of vibration due to the structural damping of the beam and is given by [11]

$$y_d(x,t) = \sum_{n=1}^{\infty} \frac{2Fl^3}{n^4\pi^4 EI} sin\left(\frac{n\pi}{2}\right) sin\left(\frac{n\pi x}{l}\right) \cos\left(w_d t\right) \exp\left(-\xi w_n t\right) \quad (6)$$

Where w_d and ξ are the damping frequency and the structural damping coefficient of the beam and are expressed as

$$w_d = w_n\sqrt{1-\xi^2} \text{ and } \xi = \frac{y_{max}}{\sqrt{4\pi^2 + y_{max}^2}} \quad (7)$$

3. Etched fiber as a sensor:

An unetched fiber is less sensitive to macrobending when compared with an etched fiber. Thus to enhance the sensitivity for macrobending, the fiber is chemically etched at the centre. When the fiber is stretched, the reduction in the cross-sectional area leads to change in refractive index. The change in core radius and index leads to a change in mode volume proportional to the induced tensile strain [12]. Therefore, the smaller cross section and refractive index changes of the etched fiber results in a larger strain and mode volume mismatch than that of an unetched fiber. In the etched region of the fiber, the cladding being thin the evanescent field in the cladding recouples with the field in the core due to strong reflection at the cladding air interface [13]. When the etched fiber experience a macrobending, the mode volume mismatch between the etched and unetched portions of fiber causes transmission power loss due to the flexural strain (field strength). The mode volume mismatch increases as the bending of the fiber increases and the intensity of light received by the photo detector decreases within the limits of bending.

In general two well known methods to reduce the fiber diameter are D-shaping and chemical etching. Among them, chemical etching method is well controllable and easy technique. For the experiment a telecommunication fiber (9/125μm core/cladd) is taken and in the middle of the fiber 1mm stretch of protective plastic coating is removed. This stripped portion is etched in 40% of HF (Hydrofluoric acid) solution for a period of 30min to reduce its diameter to 50μm. Once the etching process is terminated, the fiber is cleaned by distilled water and ethanol to remove the traces of HF, and then dried under vacuum [14, 15]. Figure 2 shows the optical microscope photograph of the unetched and etched portions of the fiber.

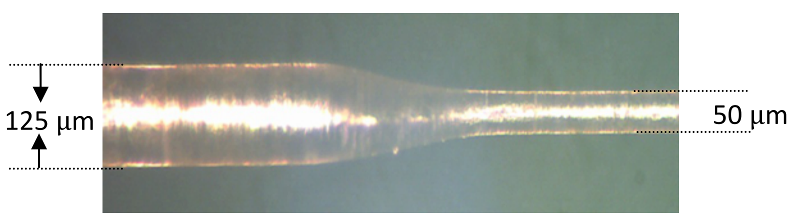

Figure 2. The unetched and etched parts of the fiber.

4. Experiment:

The schematic of the experimental setup is shown in figure 3. A spring-steel beam with length 308mm, breadth 25mm and thickness 0.5mm is taken. It is placed on two rigid knife edges with 64mm overhang. Ligth from a broadband source (1550nm) is allowed to enter from the first node to the second node of the circulator.An FBG is connected to the second node of the circulator and at the end of the FBG an index matching gel (IMG) is used to minimise the noise level and reflection from the end of the fiber. The light reflected by the FBG (1540.32nm) is transmitted from node2 to node3 of the circulator and then coupled into the centre etched fibre. The intensity of light at the other end of the etched fiber is detected by a matched photo-detector connected to a transimpedance amplifier to convert light into equivalent electrical signal with required amplification. The electrical signal from the transimpedance amplifier is acquired by the NI-6016 DAQ and processed by LabVIEW software.

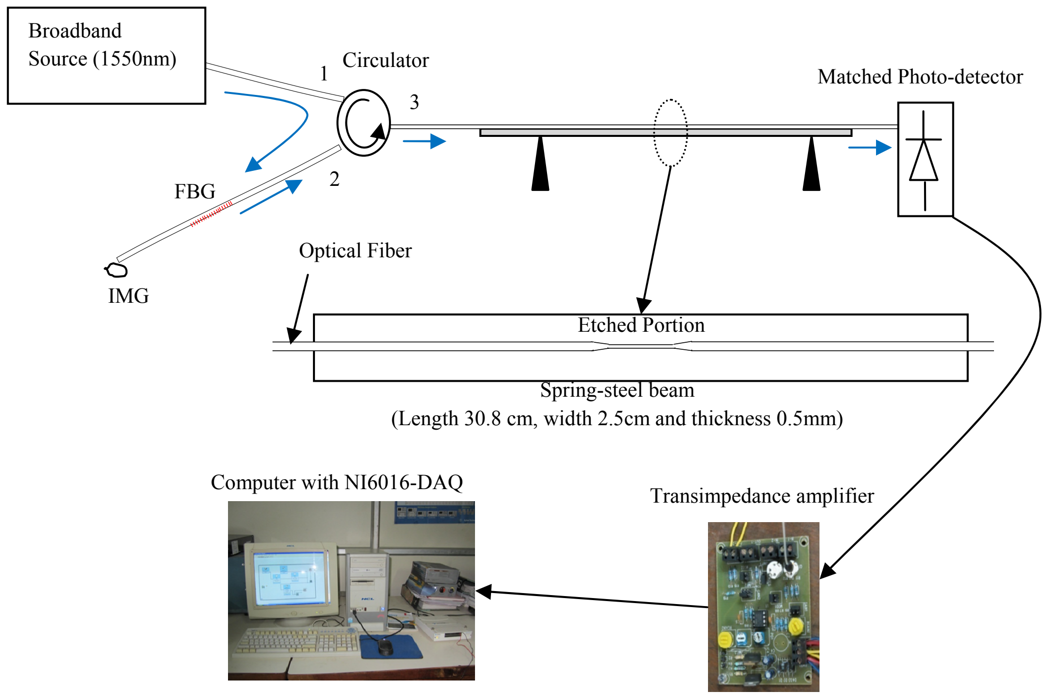

Figure 3. The schematic experimental setup of the etched vibration sensor.

With the help of a micrometer arrangement the beam is made to displace at its centre in steps of 50µm and the response of the sensor is shown in figure 4. The sensor has (figure 4) high linear response to axial displacement of 0.8mm with sensitivity of 32mV/10µm strain. The output power variation sensed for different lateral displacement is plotted in figure 5.

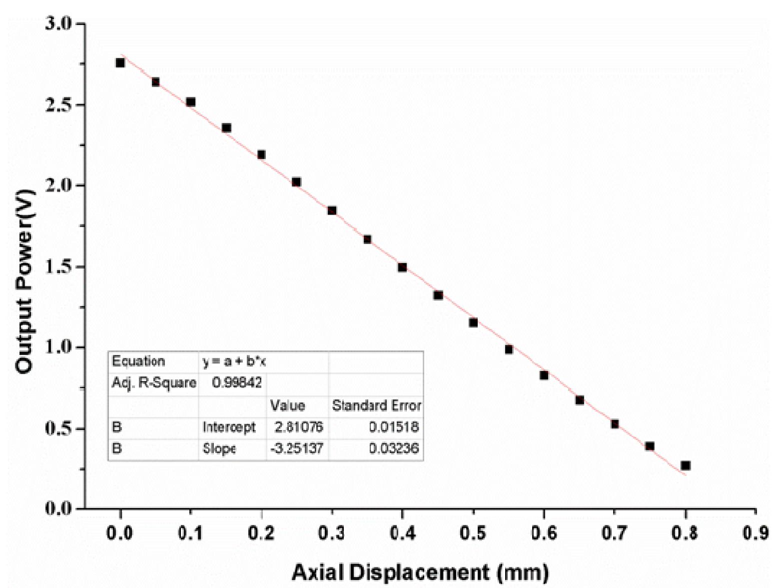

Figure 4.The sensor response for axial displacement of the beam at the centre.

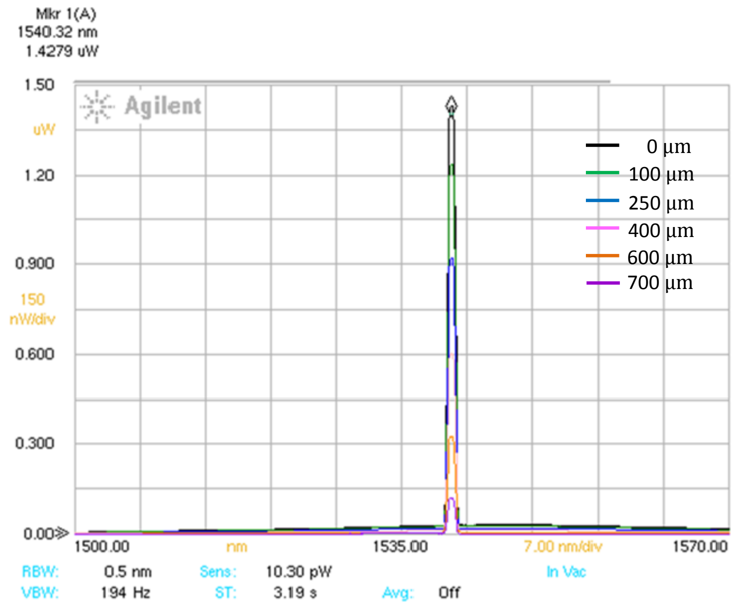

Figure 5. The output power variation for different axial displacements of the beam.

5. Results and Discussions:

The beam is subjected to bending periodically with an offset cam attached to stepper motor and the response is recorded with the data acquisition system and is plotted in figure 6. The offset portion in figure 6 shows the stability of the signal. By releasing the applied force on the beam, the response of the sensor is as shown in figure 7. The exponential decay of the amplitude of vibration of the beam after releasing the force is in good agreement with the theoretical prediction. From figure 7for the portion *a* to *b* the beam is excited by the near step force and then it overshoots to underdamped motion due to the structural damping and slowly the amplitude comes to zero with time. The FFT of time domain signal gives the frequency of vibration of the beam and it is found to be 17Hz, which matched with theoretical value from equation (7).

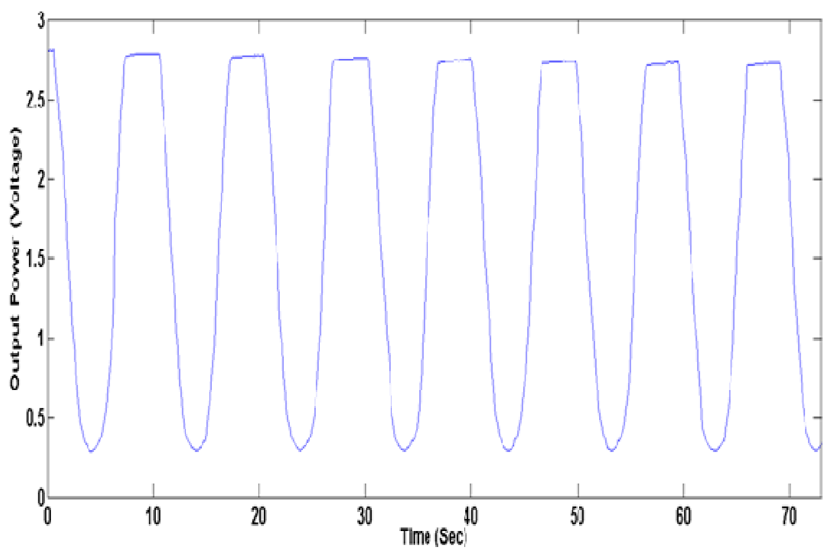

Figure 6. Response of the sensor for periodic vibration of the beam.

The time and frequency response of the beam gives the sufficient information about the health condition of the beam. The sensor is also tested for the suddenly released step force applied repeatedly and the response is as shown in figure 8. As the length of the sensor plays an insignificant role in power loss, it is recommended for real time health monitoring systems.

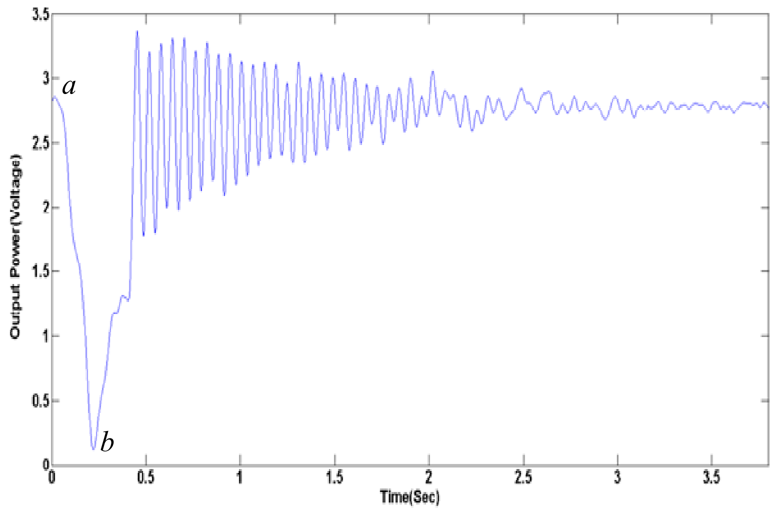

Figure 7. Response of the sensor for suddenly released force at the centre of the beam.

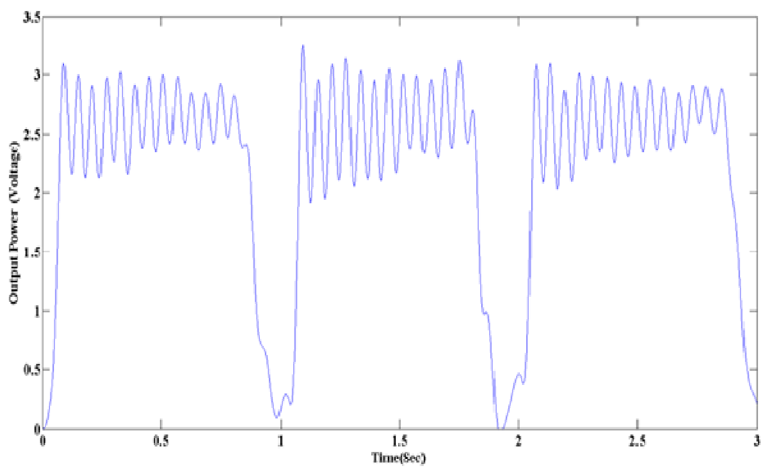

Figure 8. Repeatedly applied force to the beam and response of the sensor.

6. Conclusions:

A simple fiber optic vibration sensor was designed and demonstrated to monitor the health condition of the simply supported beam with symmetric overhang. The sensor shows high linear response of 0.8mm axial displacement with sensitivity of 32mV/10µm strain. The sensor was tested for forced vibrations of the beam such as suddenly released forces and periodic force, which would be more realistic and appropriate for real field. The time response of the beam was recorded and measured the frequency response using FFT, These responses give enough information about the state of the beam and its failure. The sensitivity of the sensor can be changed by changing the diameter of the etched fiber. The sensor has its own advantages such as simple design, economical, flexible in length, small in size. These advantages enable the sensor for remote health monitoring of the beam like structures.

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