Resonant FBG Vibration Sensors for Durable Health Monitoring Systems

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Abstract. A simple mechanism for a vibration sensor based on Fiber Bragg grating (FBG) is proposed for durable health monitoring systems. The mechanism utilizes the gravity force to allow the maximum sensitivity of the sensor into vertical direction while the minimum sensitivity for other two transverse directions. It has a high sensitivity in the vicinity of its resonant frequency. The mechanism to control the resonant frequency is based on a simple tension control. The sensor consists of an FBG cable and distributed masses to form a vibration system. The sensitivity of the sensor is more than 1µstrain/gal for vertical direction. By positively making use of the nonlinear characteristics of the sensor, no damping component is needed to the sensor. This simple sensor has been developed for damage detection of embedded structural systems such as pipelines.

Introduction
Important infrastructures such bridges and embedded pipelines need routine checkups for keeping their good functionality. However, the checkup solely depending of humans has certain limitations on the accuracy and the accessibility. In addition, the costs associated with their checkup are becoming expensive. Recently many fiber optic sensors have been proposed and developed. They have many advantages to change the human-based checkup to automatic systems. One of the most promising fiber optic sensors is fiber Bragg grating (FBG). However, the measurement of vibration using FBG may need mechanical apparatuses that transfer the vibration values into uniform strain induced in the FBG element. [1] Thus, the purpose of our research is to propose a simple and durable mechanism for FBG vibration sensors that ensure the uniform strain distribution in the FBG element.

Optical Fiber Sensor
Optical fiber sensors have been developed for many application fields. They have significant advantages compared with conventional electrical sensors such as:
- Small in size
- Durable against chemical stimulus and corrosion
- Non-explosive
- Electro-magnetically immune
- Low signal loss over long distance
These features are ideal for sensors for buried pipelines.

Principle of FBG (Fiber Bragg Grating). FBG is the optical fiber which is given the periodic refractive-index change to the core. If the refractive index of a core is $n$ and the interval of the Bragg Grating is $d$, when broad band light is applied to the FBG section, it reflects only the wavelength $\lambda$ determined by this index ratio. Therefore, the strain and the temperature arising at the FBG section can be measured by observing the wavelength of the reflective light.
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Fig. 1 Mechanism of FBG (Fiber Bragg Grating)

Tension-Based FBG Sensor

Mechanism of Proposed Sensor  The sensor we developed is so-called “Tension-Based FBG Sensor”. The acceleration sensors using FBG have been proposed for many frequency bands to have flat sensitivity over the target frequency range. However, the mechanisms supporting this feature tended to be complicated and to become large. Our proposed sensor simplifies this mechanism drastically but sacrificing flat sensitivity over the frequency of interests. The Tension-Based FBG sensor has the following features:

- Reduced production cost
- Simple mechanism
- Small size
- High sensitivity only in vertical direction
- Controllable resonant sensitivity

Initially Proposed Mechanism[2] The initially proposed Tension-Based FBG sensor consists of FBG cable and one mass as depicted in Fig. 2. However this configuration resulted in unstable sensitivity due to a mass movement along the fiber (Fig. 2 (a)). In addition, the edge the mass constitutes fragile connection. (Fig. 2 (b))

Distributed Sensor System The concentrated mass of the Tension-Based FBG Sensor was then modified to distributed mass.[2] This new configuration indeed could avoid the damage in the fiber. A typical configuration is shown in Fig. 3.

Fig. 2 Initially proposed FBG vibration sensor

Fig. 3 Tension-based FBG sensor using distributed mass

The mechanism of the proposed sensor is described below:
Parameters used are listed below:
- $m_k$: Weight of the $k$-th mass from left
- $g$: Gravity
- $E$: Young’s modulus of the optical fiber
- $A$: Cross section area of the optical fiber
- $\varepsilon_i$: $i$-th optical fiber strain from the left
- $L_0$: Distance of each mass
- $L_{all}$: All distance of the optical fiber

Assuming that the strain arising at the center is to be $\varepsilon_N$, the strain arising at the $i$-th section of optical fiber can be expressed by

$$
\varepsilon_i = \sqrt{\varepsilon_{N/2+1}^2 + \left(\sum_{k=1}^{N/2} m_k g \frac{EA}{E}\right)^2}
$$

Therefore from Eq. 1 the angle of the optical fiber is given by

$$
\sin \theta = \frac{\sum_{k=1}^{N/2} m_k g}{\sqrt{\varepsilon_{N/2+1}^2 + \left(\sum_{k=1}^{N/2} m_k g \frac{EA}{E}\right)^2}}
$$

$$
\cos \theta = \frac{\varepsilon_{N/2+1}}{\sqrt{\varepsilon_{N/2+1}^2 + \left(\sum_{k=1}^{N/2} m_k g \frac{EA}{E}\right)^2}}
$$

Using the above two equations, the horizontal length of the optical fiber $L_i$ given by
\[ L_i = \left( 1 + \sqrt{\frac{\varepsilon_{N/2+1}^2}{L_i} + \left( \sum_{k=i}^{N/2} \frac{m_k g}{EA} \right)^2} \right) L_0 \cos \theta \] (4)

The sum of \( L_i \) must be equal to the length of the whole optical fiber before fitting masses. Therefore next Eq. 5, Eq. 6 is obtained as

\[ L_{all} = 2 \sum_{i=1}^{N/2} L_i + (1 + \varepsilon_{N/2+1})L_0 \] (5)

\[ L_{all} = 2 \sum_{i=1}^{N/2} \left( 1 + \sqrt{\frac{\varepsilon_{N/2+1}^2}{L_i} + \left( \sum_{k=i}^{N/2} \frac{m_k g}{EA} \right)^2} \right) \sqrt{\frac{\varepsilon_{N/2+1}^2 L_0}{\varepsilon_{N/2+1}^2 + \left( \sum_{k=i}^{N/2} \frac{m_k g}{EA} \right)^2}} + (1 + \varepsilon_{N/2+1})L_0 \] (6)

Moreover to investigate the dynamic characteristics of FBG sensor using the distributed mass, stiffness matrix assuming infinitesimal displacement is derived and a linearized state equation is obtained. When the infinitesimal displacement \( dy \) is assumed, the increasing force at the edge in each direction can be given by

\[ df_{ixy} = EA \frac{\sqrt{\varepsilon_{N/2+1}^2 L_i^2 + (yi + dy)^2} - L_0}{L_i} \sqrt{\varepsilon_{N/2+1}^2 L_i^2 + (yi + dy)^2} - EA \varepsilon_{N/2+1} \] (7)

\[ df_{ioy} = EA \frac{\sqrt{\varepsilon_{N/2+1}^2 L_i^2 + (yi + dy)^2} - L_0}{L_0} \frac{yi + dy}{\sqrt{\varepsilon_{N/2+1}^2 L_i^2 + (yi + dy)^2}} - \sum_{i}^{N/2} m_i g \]

\[ df_{icy} = EA \frac{\sqrt{\varepsilon_{N/2+1}^2 L_i^2 + (yi + dy)^2} - L_0}{L_0} \frac{0}{\sqrt{\varepsilon_{N/2+1}^2 L_i^2 + (yi + dy)^2}} = 0 \]

From Eq.7, if linearized approximation is practiced, stiffness matrix \( K \) is obtained as

\[
K_i = \begin{pmatrix}
K_{ixx} & K_{ixy} & K_{ixz} & -K_{ixx} & -K_{ixy} & -K_{ixz} \\
K_{iyx} & K_{iyy} & K_{iyz} & -K_{iyx} & -K_{iyy} & -K_{iyz} \\
K_{izx} & K_{izy} & K_{izz} & -K_{izx} & -K_{izy} & -K_{izz} \\
-K_{ixx} & -K_{ixy} & -K_{ixz} & K_{ixx} & K_{ixy} & K_{ixz} \\
-K_{iyx} & -K_{iyy} & -K_{iyz} & K_{iyx} & K_{iyy} & K_{iyz} \\
-K_{izx} & -K_{izy} & -K_{izz} & K_{izx} & K_{izy} & K_{izz}
\end{pmatrix}
\] (8)

By defining the displacement and the velocity of each mass as state variables, the system matrix of the whole system can be obtained easily by adding the elemental system matrices. The sensitivity of the system is shown in Fig. 6.
Frequency Band Control

The resonant frequency of the proposed system can be easily controlled by changing its sensor length, tension force, mass or sag. It is interesting to note that increasing the sag of the fiber results in increasing the resonant frequency. Fig. 7 shows the sensor configuration with certain sag. Fig. 8 shows frequency response of the sensor for several sags. If the sag is negligibly small, the resonant frequency of proposed sensor is about 30Hz. Increasing the sag, it is obvious that the resonant frequency shifts to high frequency. It should be also noticed that the sensitivity is not changed by introducing the sag. This mechanism allows us an easy resonant frequency control so that we can easily move the most sensitive frequency band at the measurement site.

Fig. 7 FBG vibration sensor with sag

Fig. 8 Effects of sag on resonant frequency of the sensor

Material for Mass

Steel was used for distributed mass for the initial prototypes for the proposed vibration sensor. However, fabrication process using plastic material is much easier and more durable than the steel is the density of the plastic is equal or larger than the steel. Several materials were indeed found that this kind of feature include compound of heavy metals. We fabricated distributed mass using such plastic as shown in Fig. 9. The density is heavier than steel.
Fig. 9 Distributed mass using heavy plastic material

**Experiments**

The dynamic response of the FBG sensor was investigated by shaking table tests as depicted in Fig. 10. The results were compared with those obtained by a servo-accelerometer. Transfer functions between the servo-accelerometer and the FBG sensor are plotted in Fig. 11. It was found that the experiment results were almost the same with the analytical results in each direction. In the vertical direction, when there is sag, the resonant frequency was changed as was expected by analyses. Moreover, the sensitivity of the sensor is not decreasing by increasing the sag.

![Experiment set-up](image)

**Fig. 10 Experiment set-up**

![Transfer functions in vertical direction](image)

(a) Without sag  (b) With sag

**Fig. 11 Transfer functions in vertical direction**

Fig. 12 shows the time-series output of FBG sensor and Servo sensor in resonant frequency band. From this result, the period of output in Z direction is the twice as high frequency as the one of the servo sensor. Whichever the mass moves to plus or minus in Z direction (Fig 13), the same amount of strain is caused in optical fiber. In short, even if the absolute value of acceleration is known, the direction of vibration cannot be decided. But by using this characteristic, we may be able to identify the vibration position, if system identification and signal technique is improved.
To understand the characteristic of this sensor to a strong input, sweep vibration test was conducted. The frequency range is from 45Hz to 70Hz. The input acceleration is from 30 to 100 cm/s². The frequency of excitation was changed at a slow speed without changing the input acceleration. Fig14 is the response of this sensor to strong input. This figure expresses the relation between three elements - input acceleration, input frequency, sensitivity. It is found that as input acceleration becomes strong, the sensitivity of this sensor becomes low and resonant frequency spreads. Sensitivity becomes about 1/3 of the case for the small acceleration. This characteristic means that this FBG sensor does not need damping component as it dampens the response for the large input due to its nonlinear characteristics. This feature further simplify the mechanism of the proposed sensor.

**Concluding Remarks**

In this paper, we proposed a simple mechanism for fiber optic sensor using FBG. The mechanism uses the gravity force and sag for controlling resonant frequency. The features of the proposed sensor is summarized below:

1) The sensitivity was not decreased by increasing sag.
2) The resonant frequency can be controlled easily by adding sag.
3) The sensor has high sensitivity in the vicinity of the resonant frequency.
4) No damping component is needed as it decreases the response for the strong inputs.
5) It may be possible to distinguish between vibrations in Y and Z directions using the doubled frequency in the Z direction while the same frequency with the vibration source for the Y direction.

References