Simultaneous Monitoring of Dynamic Strain and Acceleration by New Fiber Optic Sensors

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ABSTRACT:

We have developed fiber optic strain and vibration sensors (FOSVS) suited for health monitoring of structures. A fiber optic gap sensor made of multi-mode fibers, broad-band light, two photo detectors and an FBG filter were used to compose the sensor system. The gap sensor was composed of a cantilever fiber and a reflector fiber. The axial strain of the sensor was measured from the reflected interfered signal. The amplitude of the transmitted signal through the reflector fiber was used to measure the transverse vibration of the cantilever fiber. From the experimental and theoretical results, it appeared that the sensor could measure the axial static strain and the transverse acceleration correctly. Furthermore it was proven that the FOSVS could measure dynamic strain and acceleration of a vibrating cantilever plate simultaneously. From these results, it can be concluded that the FOSVS sensor has practical capability of simultaneous measurement of strain and acceleration.

INTRODUCTION

Recently, cure and health monitoring technologies of the composite structures have been studied because they are remarkable approaches to reduce the cost and enhance the reliability [1]. Among the built-in sensors used for the purpose, fiber optic sensors are one of the most promising sensors due to their benefits of light weight, high mechanical properties, insensitivity to electro-magnetic noise and multi-functionality.

Many kinds of fiber optic sensors have been used for the studies on cure and health monitoring . An EFPI (Extrinsic Fabry-Perot Interferometer) sensor, an FBG (Fiber Bragg Grating) sensor, a B-OTDR (Brillouin Optical Time Domain Reflectometry) sensor and a fiber optic vibration sensor were applied to cure and health monitoring of composite structures [2-11]. These sensors were used to measure strain, temperature and vibration of the base structures. Especially so as to monitor structural health of

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composite panels, in-plane strain and out of-plane vibration are very important parameters. Then, we have paid attention to both an EFPI sensor and a fiber optic vibration sensor for monitoring of strain and vibration [12].

An EFPI sensor, which has an air gap, is used for both cure and health monitoring, because the EFPI is high sensitive to axial strain and insensitive to temperature. The sensor is composed of two fibers to make an air gap and the sensing part is surrounded by a thin glass tube. The interference of the reflected light from the sensor leads to the accurate gap length. On the other hand, a vibration sensor, which has the similar structure as an EFPI, can obtain transverse vibration from variation of optical loss of transmitted light. Therefore we considered that an 'air gap' sensor could measure strain and vibration by detect both reflected and transmitted lights simultaneously.

In the present paper, we propose FOSVS (Fiber Optic Strain and Vibration Sensor), which measures the axial strain and transverse acceleration simultaneously. To verify the capability, several experiments and analyses were conducted.

THEORY OF FOSVS

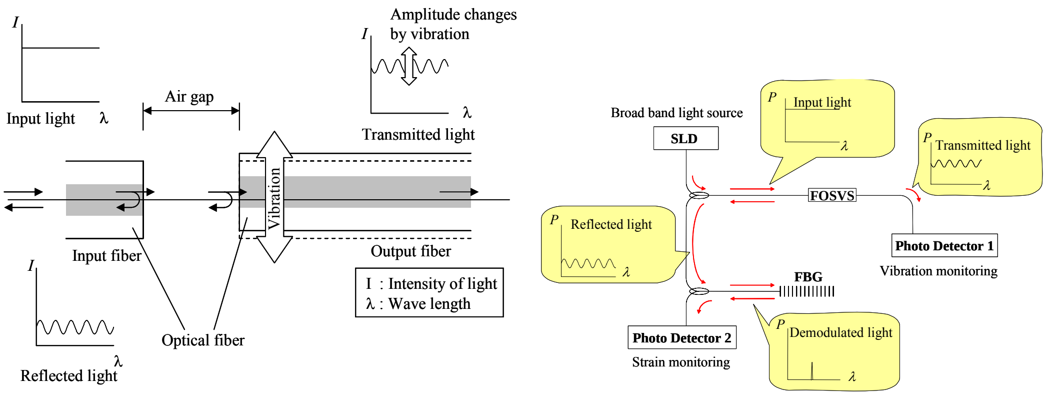
Optical system

The FOSVS composes Fabry-Perot interferometer by two optical fibers and air gap as shown in Fig. 1(a). The figure shows behaviors of reflected and transmitted lights from the sensor. The reflected light is an interfered light between the light reflects at the end of the input fiber and, at the end of the output fiber. The interfered signal is a sinusoidal function of the air gap length. On the other hand, the transmitted light power decreases when the axial slippage increases by transverse vibration.

The optical system for the FOSVS is illustrated in Fig. 1(b). The interference of the transmitted light through the air gap is canceled by using a broadband light source. The reflected light is demodulated by using an FBG narrow-band filter. The axial slippage almost never affects the reflected light and the strain measurement, since the refractive indices of the core and clad of the optical fiber are almost the same.

Theory of strain measurement

The FOSVS has a Fabry-Perot interferometer for strain measurement. The reflected light power I changes when the air-gap changes. The reflected power is calculated by the following equation.



(a) Structure of FOSVS (b) Optical system

Figure 1: Optical system and structure of FOSVS.

$$I_r = \frac{F \sin^2 \delta/2}{1 + F \sin^2 \delta/2} I_0, \quad F = 4r^2 / \left(1 - r^2\right)^2, \quad \delta = 4\pi\, d/\lambda + \phi\,. \tag{1}$$

Where, I_0 is the intensity of the input light, F is the finesse, r is reflectivity between air and a glass, d is a length of the air-gap, ϕ is a phase shifts at the end of optical fibers, λ is a center wavelength of an FBG filter in the optical system used in this study. The reflected light has an interference period d_0, which is

$$d_0 = \frac{\lambda}{2}\,. \tag{2}$$

Then, d_0 can be easily obtained by counting fringes of the reflected light.

The theory of vibration measurement

The output of the vibration sensor can be related to the acceleration and is considered to be a cantilever beam of the length l subjected to acceleration loads. The deflection y of the beam can be easily obtained from the elastic beam theory [14] as

$$y\left(a, \Omega_0, l\right) = a \sum_{i=1}^{N} \frac{W_i\left(l\right) \bar{W}_i\left(l\right)}{l\left(\omega_i\left(l\right)^2 - \Omega_0{}^2\right)} \quad \text{and} \quad \bar{W}_i\left(l\right) = \int_0^l W_i\left(x\right) dx\,, \tag{3}$$

where, a is acceleration, Ω_0 is frequency of forced vibration, ω_i are natural frequencies of the cantilever fiber and W_i are modal functions of natural vibration modes. From the equation (3), it is understood that the axial slippage has a linear relationship with acceleration.

The transmitted light power $\bar{I}$, which is normalized by the value at zero values of axial slippage and air-gap, was plotted against the axial slippage h in Fig. 2. The relationship between the transmitted light power and the axial slippage in the figure was measured for the multi-mode fiber of the core diameter 50μm. From the figure, it was found that the transmitted power decreases with the axial slippage increases and the cavity length hardly affected the relationships. We can obtain the axial slippage from the output light from this relationship.

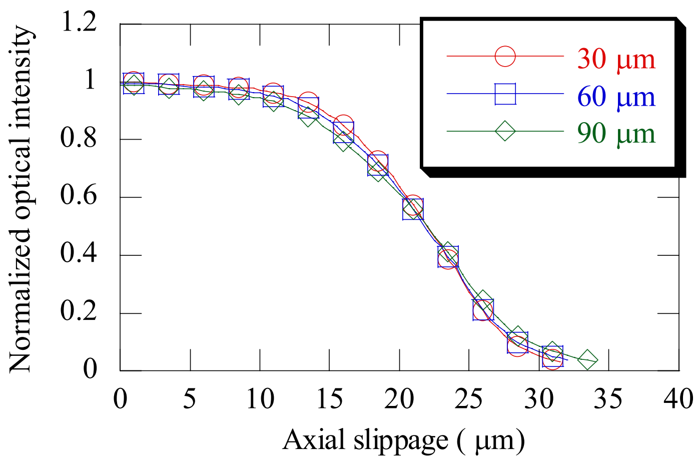


Figure 2: The relationships between transmission power and axial slippage for multi-mode optical fiber (cavity lengths are 30, 60 and 90 μm).

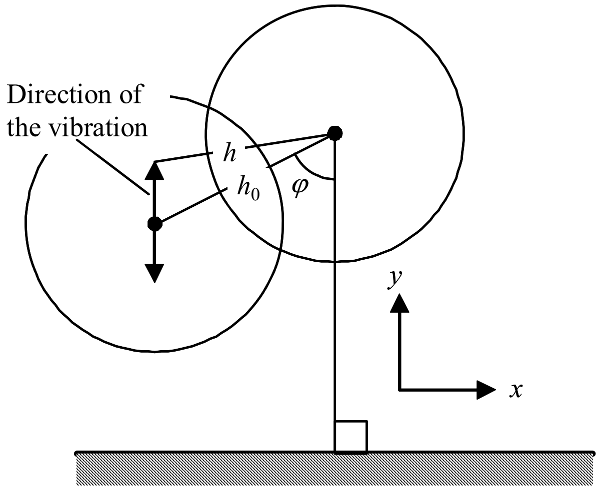


Figure 3: Initial axial slippage of the vibrated sensor.

The initial axial slippage

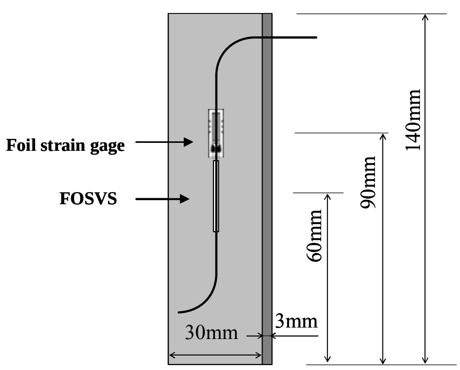
The relationship in Fig.2 was measured with the in-axial plane mode, where the plane contains the axes of the input and the output fibers. In the practical use, the vibration mode may be the off-axial plane mode with rotating angle of the initial slippage direction φ as shown in Fig.3. In addition, the sensor has initial axial slippage h_0 in order to obtain high sensitivity. Therefore, the initial slippage parameters φ and h_0 were very important to decide the precise relationship between the optical power and acceleration.

At first, we measured the angle of the initial slippage direction. We can easily set φ to zero, that is, the in-axial plane mode, by rotating the sensor so that the transmitted light power becomes maximum or minimum. From the optical output at the in-axial plane mode, the initial axial slippage can be measured. the initial slippage direction can also be obtained by counting angles from the in-axial plane to the sensor plane.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Static strain measurement

The tensile test of an aluminum plate with the attached FOSVS and strain gauges was



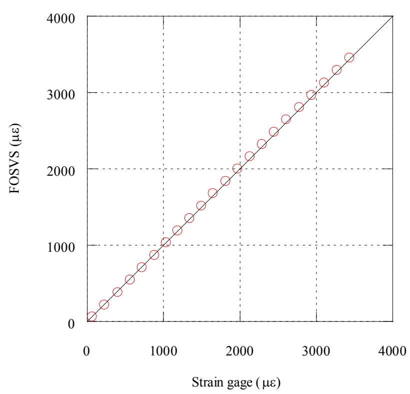


Figure 4: The specimen for the tensile test. Figure 5: The results of the tensile test.

conducted to confirm the FOSVS function for strain measurement. The specimen with the sensors was illustrated in Fig.4. The base plates were stretched by a universal testing machine (Shimadzu, Autograph).

Figure 5 shows the relationship between the strain measured by the FOSVS and, by strain gauges. From the figure, it was found that strain by the FOSVS agreed very well with that by strain gauges. Therefore, it can be said that the FOSVS can measure precise static strain by this system while the reflected right power is low. Since the effect of the air-gap length on the loss of optical power was very low for multi-mode fibers, we can expect the sensor can measure displacement of over 100μm, which corresponds to 10000με when the gauge length is 10mm.

Vibration test under static tensile strain

The vibration tests were executed to confirm the FOSVS function of accelerometer with applying tensile strain. The schematic view of the experimental set-up for this test is shown in Fig.6. The specimen is a small epoxy base plate where the FOSVS was adhered. The specimen was fixed by steel jigs which can apply static strain and vibration to the specimen. The specimen vibrated vertically by an actuator (Brüel & Kjær, Type 4810). We applied sinusoidal vibrations to the specimens. The acceleration applied to the specimen was measured by an accelerometer (Brüel & Kjær, Type 8001). The characteristic parameters of FOSVS were l = 9.5 mm, l_g = 10 mm and d = 50 μm.

Figure 7 shows the accelerations measured by the FOSVS under 990 με and the accelerometer. From the figure, it appeared that the both results agreed very well with each other. We conducted the tests at different applied strains and frequencies. The measured frequency responses of the sensor were shown in Fig. 8. The ordinate is the sensor sensitivity to the acceleration and the abscissa is applied frequency. The applied strains were 0, 990, 2100, 3300 με. The theoretical frequency response curve of the FOSVS calculated by the equation (3) was also plotted in the figure. From the figure, it was found that the experimental data and the theoretical curve agreed well with each other. From these results, it appeared that he FOSVS could measure correct acceleration and the frequency response of the FOSVS sensor is predictable by the simple elastic beam theory.

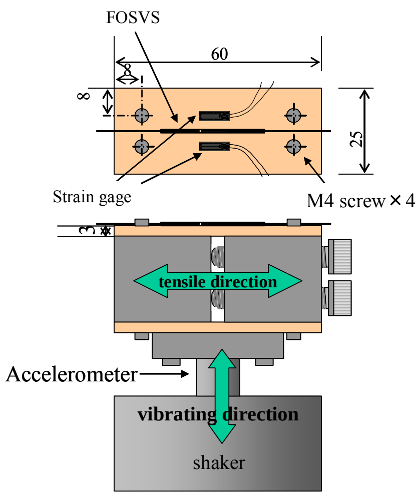


Figure: 6 The experimental set-up for vibration tests under strain.

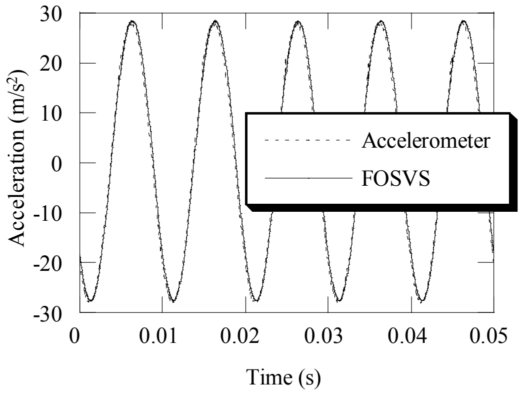


Figure 7: Accelerations measured by FOSVS and accelerometer (100Hz, 990 με).

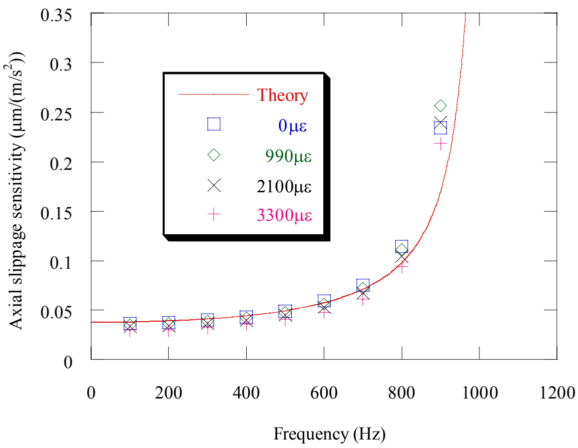


Figure 8: The frequency responses of FOSVS.

Simultaneous measurement of strain and acceleration of the vibrating plate

The vibration tests of aluminum cantilever plates were executed to confirm the simultaneous measurement function of acceleration and strain. The experimental set-up was illustrated in Fig.9. The FOSVS was adhered at the aluminum plate and strain

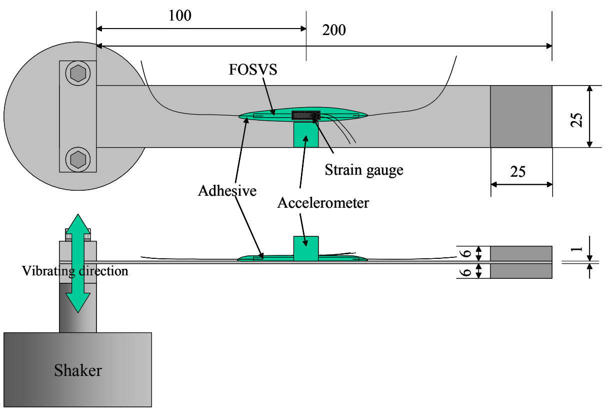


Figure 9: The specimen for vibration test of cantilever plate.

gauges were also adhered neighboring the FOSVS. An accelerometer was placed next to the FOSVS to measure acceleration.

Acceleration and strain measured simulutaneously by the FOSVS were plotted against tine in Fig.10. The acceleration measured by the accelerator and strain done by the strain gauges were also plotted in the same figures. From the results of acceleration measuremet, it was found that the acceleration by the FOSVS almost agreed with that by the accelerator. Since the bending accerelation was affected by modal shapes and location, it was thought that the difference between the FOSVS and the accelerator was coused by the difference of the sensor size.

As for the results of strain measurements, the results of the FOSVS were different from the strain gauges. In order to investigate the reason, a high power FP-LD was used

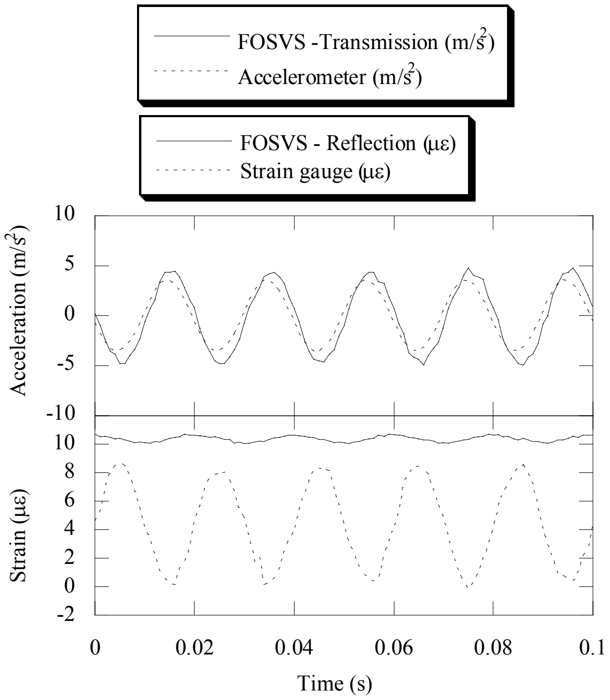


Figure 10: Time histories of acceleration measured by accelerometer and FOSVS, strain, and reflected light power.

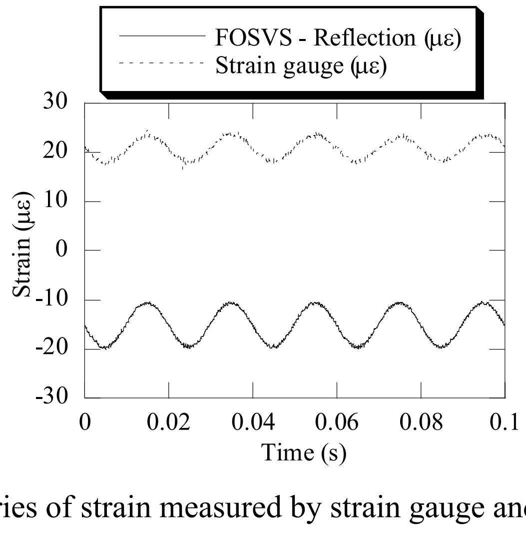


Figure 11: Time histories of strain measured by strain gauge and FOSVS with FP-LD.

as a light source instead of the broadband SLD and the only strain measurement was conducted. The results of the strain measurement by the FOSVS was shown with the measured results of the strain gauges in Fig.11. Since the figure showed that the strain amplitudes measured by both sensors were almost the same as each other, it can be said that the error of strain function of the FOSVS shown in Fig. 10 was a dynamic sensitivity problem of the detector due to poor light power. Therefore, it was found that a high-power broadband light source or lower loss of connections of optical fibers are required to avoid the error.

CONCLUSIONS

In this study, we developed the FOSVS using multi-mode optical fibers which could measure both strain and acceleration correctly. From the experiments, it was found that static strain could be measured by the FOSVS correctly. The experimental results of acceleration measurement of the FOSVS under static strain agreed very well with that of an accelerometer. Furthermore, it appeared that the resonance characteristic of the FOSVS is predictable. Finally, the experimental results of measurement of the vibrating plate proved that the FOSVS could measure dynamic strain and acceleration simultaneously.

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