VIBRATION AND MODE SENSING OF A COMPOSITE BEAM USING FIBER BRAGG GRATING SENSOR ARRAYS

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SUMMARY: This paper discusses the use of fiber Bragg grating arrays for structural vibration sensing and modal analysis. By the use of recently developed wavelength-swept fiber laser(WSFL), we constructed two sensor arrays composed of 9 FBG sensors. For an accurate measurement of wavelength shifts of FBG sensors, a signal processing board with an electric circuit based on time-interval counting was developed. This circuit board supplies the tremendous enhancement of real-time signal processing program using Labview software for data storage and visualizing of the signals from sensors. To demonstrate the performance of the sensor system, real-time dynamic strain sensing of 9-points on composite beam was executed. From the acquired strains, natural frequencies and strain measured mode shape of the composite beam were calculated. The experimental results of natural frequencies and mode shapes showed a good agreement with numerical results by ABAQUS.

KEYWORDS: WSFL, FBG sensor system, strain measured mode shape

INTRODUCTION

Optical fiber sensors have considerable research interest recently. They can easily embedded or attached to the structures and are not affected by electro-magnetic field. Also, they have the flexibility of the sensor size(μm~km) and are very highly sensitive. These advantages of a FOS make it to be the potential solution for sensor systems of smart structures[1].
Among several types of FOS, FBG sensor has lots of advantages over other FOSs. FBG sensor is easy to multiplexed and has many advantages of linear response, absolute measurement, independence of intensity fluctuation induced by the source, etc. FBG sensors based on the wavelength division multiplexing(WDM) technology attract considerable research interest and appear to be ideally suitable for structural health monitoring.
For the interrogation of FBG sensor system, various schemes have been reported and these schemes have their own merits and demerits. Recently, the interrogation technique based on the WSFL was developed [2]. This technique offers several attractive features over other interrogation schemes. First, it provides for high signal powers, since the full source is available during the measurement of a given grating's Bragg wavelength. Second, the broad source tuning range and narrow instantaneous spectral line width allow for a large number of individual elements within the array. Third, simple signal-processing schemes can be employed, since wavelength-encoded sensor signals appear in the time domain that each sensor's timing relative to the start of the wavelength sweep is determined by Bragg wavelength of each corresponding grating.

In this study, we constructed FBG sensor system using a WSFL and the signal-processing eletric circuit and program. Strains of a composite beam by impact vibration were measured real timely using the developed sensor system. From the acquired strains, mode shapes of a beam were also calculated and compared with the numerical results by ABAQUS.

FBG Sensor System with WSFL

A fiber Bragg grating is a periodic, refractive index perturbation that is formed in the core of an optical fiber by exposure to an intense UV interference pattern. When temperature changes or mechanical strains are applied to the FBG sensors, Bragg wavelength is changed. The accurate detection of Bragg wavelength shift is important to strain measurement. For the purpose, the WSFL is constructed and employed to the present FBG sensor systems. The WSFL has a scanning tunable filter in the cavity to sweep the laser output wavelength in time continuously and repeatedly over a range of a few tens of nanometers. By measuring the reflected pulse timing characteristics and employing simple signal processing schemes based, for example, on time interval counting and peak detection, one can deduce the instantaneous Bragg wavelength of the individual grating within the array.
Fig. 1(a) shows a schematic of the configuration of the WSFL and (b) the grating arrays with reference FBGs and a Fabry-Perot(F-P) etalon. The WSFL was in a unidirectional ring configuration with isolators, a 3-*dB* output coupler, and an Er^{3+} - doped fiber pumped by a laser diode at 980 *nm*. A F-P tunable filter was used as the intracavity scanning filter and had 3 *dB* bandwidth of 0.27 *nm* and a free spectral range of 58*nm*. We modulate the F-P filter with a triangular waveform to produce a wavelength sweep over 40*nm* from 1525*nm* to 1565 *nm* at possible repetition rate, in this study 280*Hz*.
The laser output is directed into two sensor arrays and two reference gratings(λ_{01} =1529.44 *nm*, λ_{02} =1532.47 *nm*) for temperature compensation. It is possible to expand sensor arrays more using couplers and detectors aided by high signal power of WSFL output. The laser output is also directed into F-P etalon which is used as a wavelength guide correcting non-linearity by the PZT of F-P tunable filter. Since the F-P etalon has 1*nm* interval between its valleys, we can calculate the wavelength shift of FBG sensors matching the sensor signals to F-P etalon signal.

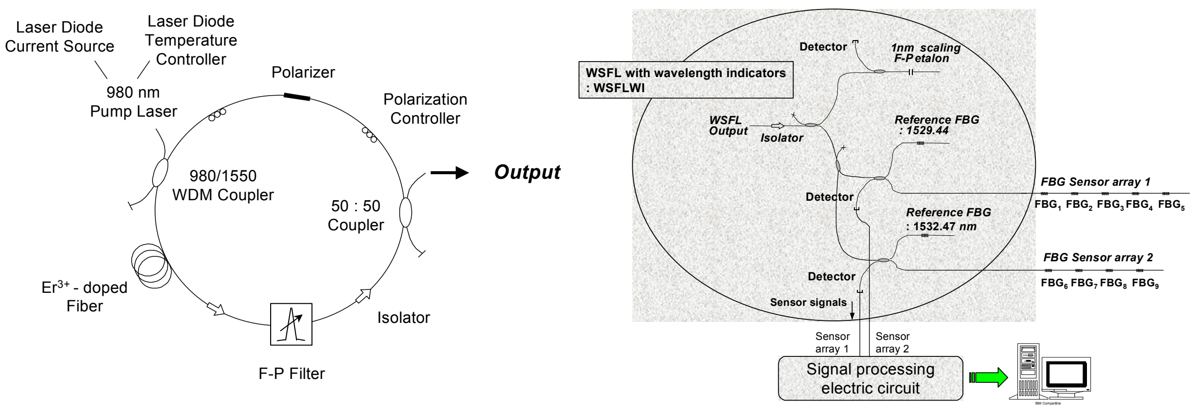

Fig. 1 Configuration of (a) the wavelength-swept fiber laser and (b) the grating sensor array.

Real-Time Signal Processing Scheme

As shown in Fig.1 (b), the sensor signals of each sensor arrays are measured with the photo detector. These sensor signals are wavelength-encoded signals in time domain as shown in Fig. 2(a). Sensor array one has five FBG sensors and sensor array two has four FBG sensors. The number of FBG sensors in one array can be expanded. Simple signal processing scheme is utilized to measure the shift of each sensor's Bragg wavelength; peak detection and time interval counting [3]. The analog voltage differentiation circuit and zero-crossing comparator execute peak detection. At peak point of the sensor, the derivative signal crosses zero voltage and voltage comparator generates digital pulse signal such as rising edge (0 V to 5 V) as shown in Fig.2(b).

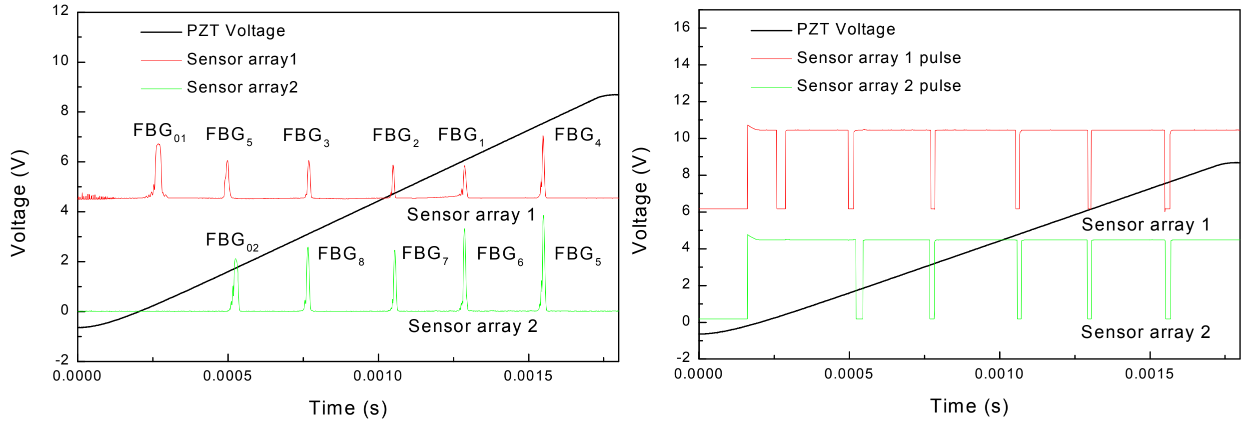

Fig. 2 (a) Sensor array signals. (b) Processed signals by electric circuit.

Since these sensor signals are changed to digital signal, it is possible to count time-interval between rising edges, i.e. peaks of FBG sensors, by high speed counter (in this study, 20*MHz*) and the counted numbers are transferred to the personal computer.

Real-Time Strain Monitoring Program

The counted number by 20*MHz* counter means the time-interval between FBG sensors. By calculating the counted number of each sensor from reference sensor and matching the counted number of each sensor to grid counts of F-P etalon with 1nm interval, the wavelength-shift of each sensor can be calculated. When FBG sensors are in the same environmental temperature, the strain at sensing point is calculated by following simplified relation between strain and Bragg wavelength-shift.

$$\varepsilon = \frac{1}{(1-p_e)}\frac{\Delta\lambda_B}{\lambda_B} \tag{1}$$

$$p_e = \left(\frac{n^2}{2}\right)\left[p_{12} - \nu(p_{11} + p_{12})\right] \tag{2}$$

where p_e (=0.225) is the photoelastic constant and measured by an experiment [4].

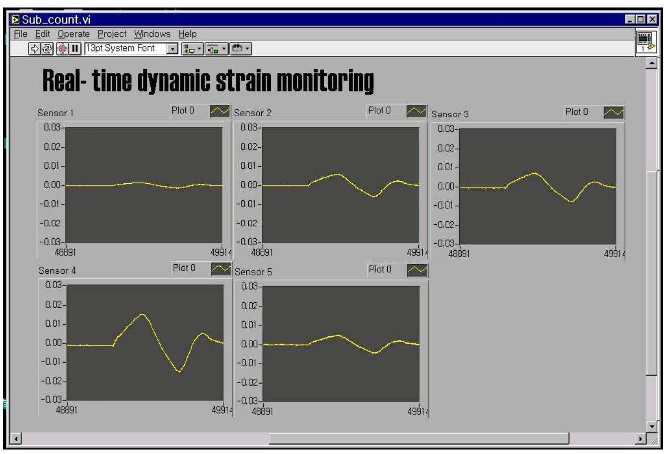

Fig. 3 Real-time strain monitoring window.

Strain calculating procedures were programmed by Labview software and executed in real-timely. Fig. 3 shows a real time window for strain monitoring, which displays the histories of five FBG sensor's strains in one array. The sensor system with this program showed a good strain resolution less than 10 $\mu\varepsilon$. Sensors were attached on the surface of a composite beam. Also, this program was constructed to store the calculated strain data and could be expanded to monitor the more sensor arrays.

Vibration Sensing of a Composite Beam

Mode sensing of a structure is performed by modal analysis. In general, modal testing needs frequency response function (FRF), i.e. the transfer function between input and output. From the strain at fixed sensing point by the impact vibration, we can acquire the FRF of the sensing point referenced to the impact point. It is also possible to acquire the same result by fixing sensing point and changing impact point. Comparing the FRFs of sensing points, we can calculate mode shape of a structure. Since FBG sensor has an advantage of multiplexing, all strain data can be acquired simultaneously by just one impact or excitation. Also, FBG sensor does not have mass-concentration effect. By this powerful multiplexing ability of FBG sensor, we can measure the strain measured mode shape of a structure.

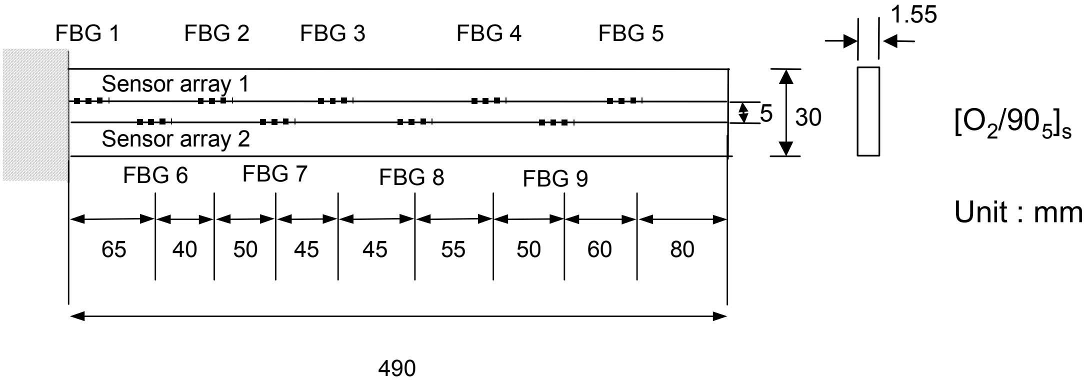

Fig. 4 Configuration of the specimen for free-vibration test.

To demonstrate the vibration and mode sensing using FBG sensors, the impact vibration test of a composite beam was carried out. Fig.4 shows the configuration of the composite beam $[0_2/90_5]_s$ fabricated using graphite/epoxy prepreg. Sensor array one has five sensors and sensor array two has four sensors.

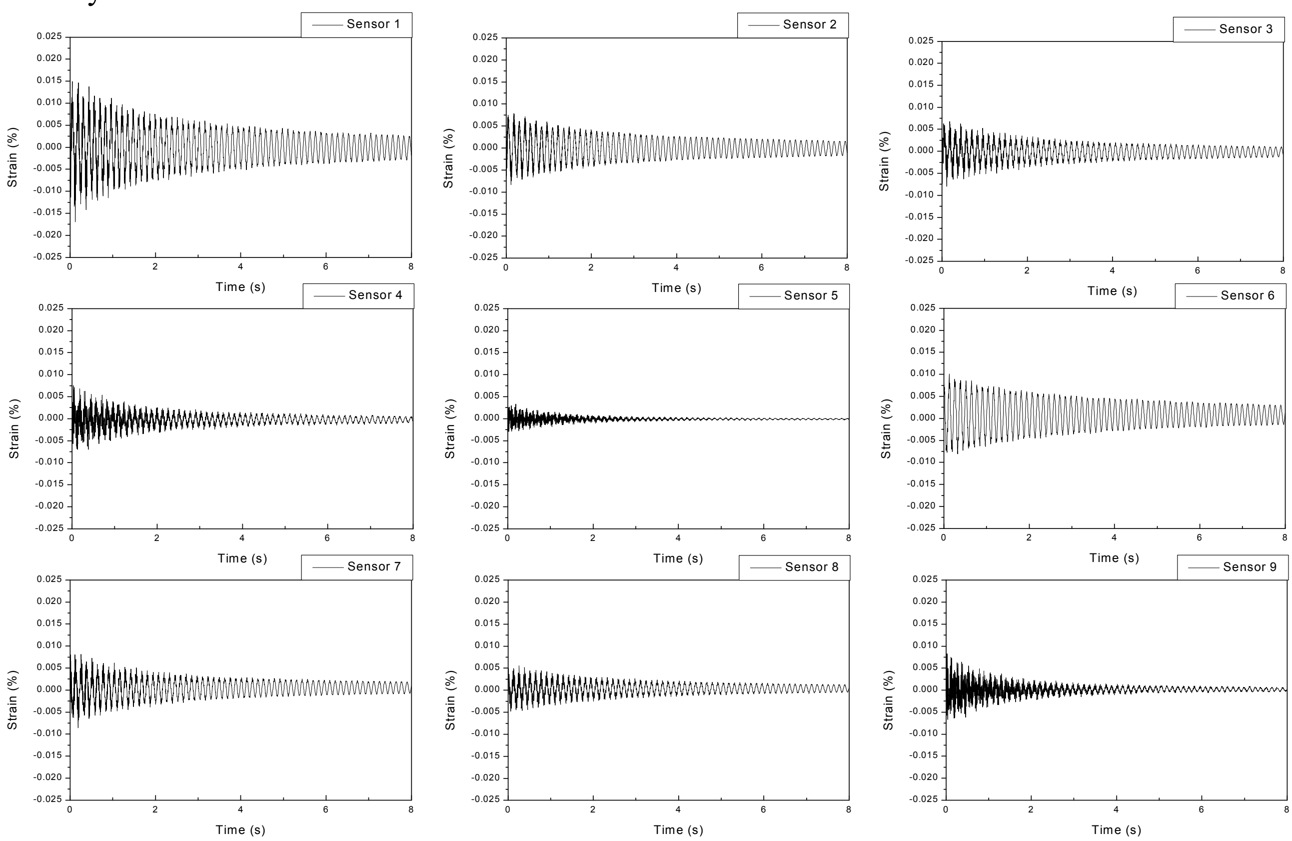

Fig. 5 Strain histories of FBG sensors in time domain.

The locations of FBG sensors were selected to represent the strain based mode shape of a beam correctly. FBG sensor two is placed such that the second mode of the beam has zero value of strain in that point and FBG sensor six and eight are placed such that the third mode of the beam has zero value of strain. When the impact hammer hits some point near the root of the beam, the strain histories of nine FBG sensors are stored to PC. Since the repetition rate of F-P filter is 280*Hz*, FBG sensor can measure vibration frequency up to 140*Hz* which is Nyquist frequency. Fig. 5 shows the strain histories of nine FBG sensors by impact vibration. All experimental procedure including strain calculation, visualizing and data storage is performed in real-time processing.

Mode Shapes of a Composite Beam

Mode shapes of a composite beam can be calculated from the strain histories of nine FBG sensors based on modal analysis. To guarantee the experimental exactness, experimental natural frequencies and strain based mode shapes were compared to the results analyzed by ABAQUS. Table 1 shows comparison of natural frequencies between experiment and analysis.

Mode	Experiment	Analysis
1st	7.72 *Hz*	7.93 *Hz*
2nd	47.85 *Hz*	49.68 *Hz*
3rd	134.12 *Hz*	139.07 *Hz*

Table 1. Comparison of natural frequencies

In frequency domain, all FBG sensors in a beam have the same values of natural frequencies, i.e. 7.72 Hz, 47.85Hz, 134.12 Hz. As shown in Table 1, the experimental result shows a good agreement with the results analyzed by ABAQUS.

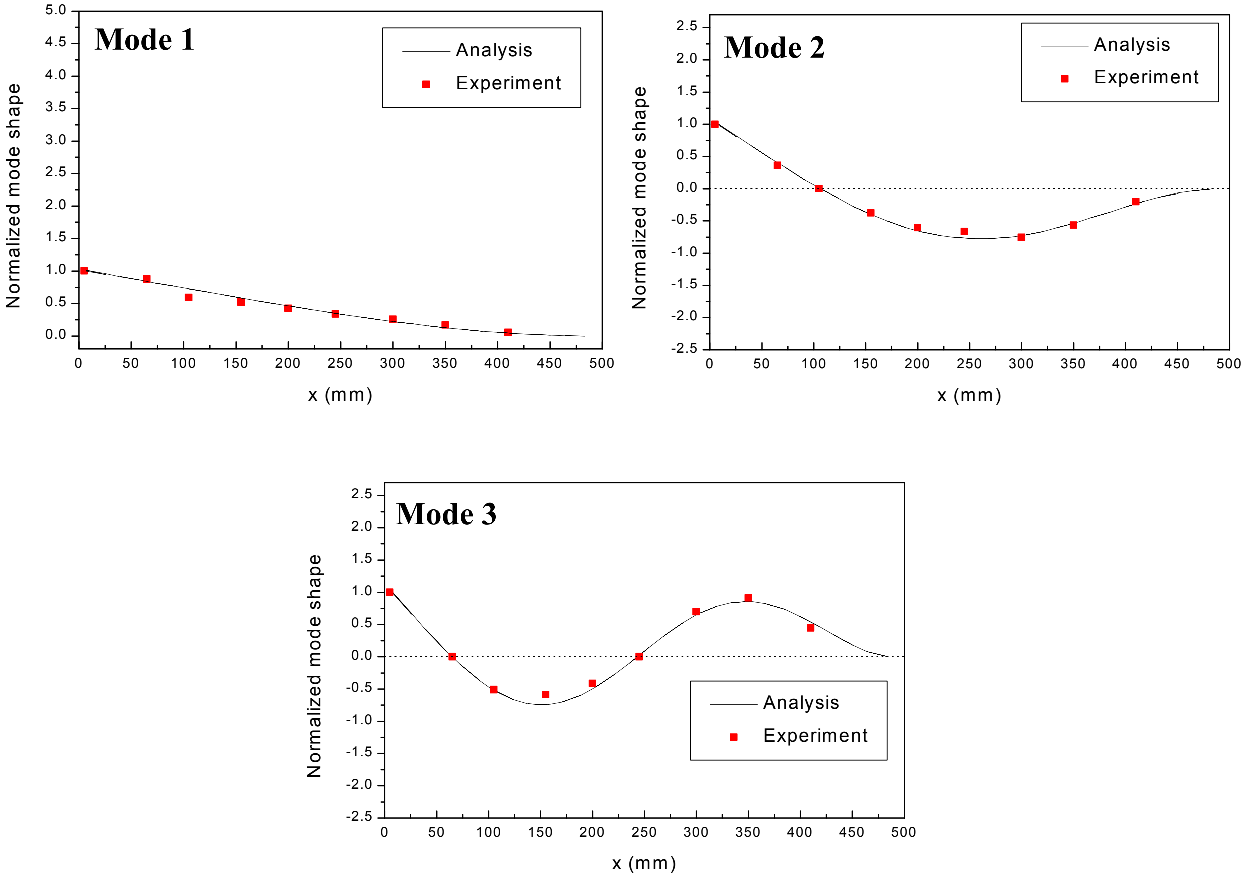

Fig. 6 Normalized strain based mode shapes of a composite beam.

Fig.6 shows strain measured mode shapes measured by nine FBG sensors and the numerical results by ABAQUS. The experimental mode shapes show a good agreement with the mode shapes by ABAQUS.
There are some differences of natural frequencies and mode shapes caused by several reasons between the experiment and the analysis. First, the imperfection of material properties and measurement of beam dimension may cause the differences of natural frequencies. Second, the gauge length of FBG sensors can cause the difference of mode shapes. Since the gauge length of FBG sensor is 1 *cm*, there is a possible error on the location of sensor; from –0.5 *cm* to 0.5 *cm*.

CONCLUTIONS

In this study, we constructed FBG sensor system using WSFL. For the real-time signal processing, the electric circuit and GUI program are also developed. The sensor system showed a good strain resolution and had properness to real-time strain measurement. Using the sensor system and nine FBG sensors, real-time dynamic strain sensing of composite beam was executed. Experiment shows that the constructed sensor system could successfully measure natural frequencies and strain based mode shapes of structures. It is also expected that this sensor system can be applied to real structure for damage detection by vibration technique, which determines the damage of a structure from changes of natural frequency and mode shape.

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