Strain Monitoring of Smart Bridge Using Fiber Bragg Grating Sensor System with Wavelength-Swept Fiber Laser

Chang-Sun Hong \(^a\), Chi-Young Ryu \(^a\), Bon-Yong Koo \(^a\), Chun-Gon Kim \(^a\), Seok-Hyun Yun \(^b\)

\(^a\)Department of Aerospace Engineering
\(^b\)Department of Physics
Korea Advanced Institute of Science and Technology (KAIST),
373-1, Kusong-dong, Yusong-gu, Taejon, 305-338, Korea

ABSTRACT

In this paper, we present an improved fiber Bragg grating (FBG) sensor system using a wavelength-swept fiber laser (WSFL). The WSFL provides unique and functional output characteristics useful for sensor interrogations. Proper monitoring of measurands in FBG sensor systems requires accurate measurement of the Bragg center wavelength, and the ability to track rapid shifts of the wavelength. For the purpose, we constructed a signal processing board with an electrical circuit and real-time signal-processing program using Labview software for storage and visualizing of the data. To improve its ability to acquire massive sensor signals, multi-channel sensor arrays were also constructed. The constructed FBG sensor system using WSFL and the real-time signal-processing program could successfully measure the strains of a composite laminated beam at nine sensing points. As a practical application of infrastructure, we demonstrate four FBG sensors in an optical fiber were used to monitor strains of the smart bridge model. When the smart bridge shows the response of near certain level of strain, the bridge tells early warning sound. This early warning system could give you time to undertake remedial works on bridges before the catastrophic disaster.

Keywords: Fiber Bragg grating sensor system, wavelength-swept fiber laser, real-time signal-processing, strain monitoring, smart bridge model, early warning system

1. INTRODUCTION

Most of the conventional damage-assessment and nondestructive inspection methods are time-consuming and are often difficult to implement on hard-to-reach-parts of the structure. For these reasons, built-in assessment system must be developed to monitor constantly the structural integrity of critical components. Measuring structural response in the form of strains and deflections is of great interest.

Optical fiber sensors (OFS) have shown a potential to serve real time health monitoring of the structures. They can be easily embedded or attached to the structures and are not affected by the electro-magnetic field. Also, they have the flexibility of the sensor size (µm–km) and very highly sensitive. These advantages of OFS make it to be the potential solution for sensor systems of smart structures\(^1\). There are several types of OFS based on the intensity of light, interferometer and FBG methods. Two types of OFS with the most promise at this time are interferometer sensors and FBG sensors. Michelson and Fabry-Perot (F-P) interferometer sensors are typical of interferometer sensors\(^2,3\). Michelson and EFPI sensors have some drawbacks and limitations such as 2\(\pi\) ambiguity, automated fabrications, multiplexing and so on. Moreover signal drifting and beating problems occur especially in case of Michelson interferometer. On the other hand, FBG sensor is easy to be multiplexed and has many advantages of linear response, absolute measurement, 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 of infrastructures. As the spectral signature renders the measurement free from intensity fluctuations, it guarantees reproducible measurements despite optical losses due to bending and/or connectors.

* Correspondence: Email: cshong@kaist.ac.kr; WWW: http://smartech.kaist.ac.kr; Telephone: 82-42-869-3712; Fax: 82-42-869-3710
Proper monitoring of measurands in FBG sensor systems requires accurate measurement of the Bragg center wavelength, and the ability to track rapid shifts of the wavelength especially in the structures under dynamic loading. Various interrogation schemes have been reported for the detection of small Bragg wavelength shifts based on the combination of a broadband source and a wavelength-dependent receiver. LED’s, amplified spontaneous emission sources and ultrashort-pulse lasers are typically used as broadband sources. For wavelength-dependent receivers, scanning tunable filters and unbalanced interferometers have been employed. However, these schemes have shown some drawbacks associated with low signal powers by using a narrow spectral slice from a broad source spectrum. Moreover, these results showed poor spectral resolution determined by the resolution of the tunable filter or the spectrometer itself. Recently, the interrogation technique based on the WSFL was developed. This technique offers several attractive features. First, it provides for high signal powers, since the full source output 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.

In this study, we constructed a FBG sensor system using a WSFL and a signal-processing board with an electrical circuit. In order to monitor the structural strain real-timely, the signal-processing program was constructed using Labview software for storage and visualizing of the data. For the verification of the system’s performance, the experiment of dynamic strain measurement of a composite laminated beam was carried out. Finally, as a practical application of infrastructure, four FBG sensors in one optical fiber were used to monitor strains of the scale down bridge span. When the strain from FBG sensors of the bridge reaches a critical level of strain, the FBG sensor system tells early warning sound. This early warning system could give you time to undertake remedial works on bridges before the catastrophic disaster.

2. FBG SENSOR SYSTEM

2.1. Construction of a WSFL and sensor arrays with reference sensors

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 system. 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. When the WSFL output is directed to the grating array, the reflected optical signal consists of a series of pulses in the time domain whose timing relative to the start of the wavelength sweep is determined by both the Bragg wavelength of each corresponding grating and the position of each grating within the array. By measuring the reflected pulse timing characteristics and employing simple signal processing schemes based, for example, on time interval counting or peak detection as in this study, one can deduce the instantaneous Bragg wavelength of the individual gratings within the array.

Fig. 1(a) shows a schematic of the configuration of the WSFL and (b) the grating arrays with reference FBGs and an F-P etalon. The WSFL was in a unidirectional ring configuration with isolators, a 3-dB output coupler, and an Er3+-doped fiber pumped by a laser diode at 980 nm. An F-P tunable filter was used as the intracavity scanning filter and had a 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 the output wavelength over 40 nm from 1525 to 1565 nm at a 130 Hz repetition rate. The laser output was directed into two arrays of sensing gratings and reference gratings (λ01=1529.44 nm, λ02=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 F-P etalon whose reflected signal has 1 nm interval between each valley was fabricated for the multi-beam interferometer. Since the general PZT has a hysteresis, the PZT of an F-P tunable filter may have non-linearity against linear modulation signal. Errors happen to be caused from this phenomenon could be corrected by an F-P etalon. The optical signal of multi-beam interference of an F-P etalon is used for a grid line that has a same spacing of wavelength. In this study, we manufactured the F-P etalon to have an interval of 1 nm wavelength between valleys of the reflected signal. If the FBG known its Bragg center wavelength is located anywhere in the grid line of wavelength, a coordinate of wavelength could be generated. The information from the reference FBG and the F-P etalon is used for signal processing of strain measurement.

Fig. 2(a) shows the laser output signal seen with a fast (50 MHz) oscilloscope and detector system and illustrates the pulsed nature of the output; Fig. 2(b) shows the peak-hold optical spectrum. The triangular waveform shown in Fig. 2(a) is the 130 Hz electrical signal that was applied to the scanning filter. As the voltage of the signal was swept upward (downward), the output wavelength increased (decreased). By appropriate alignment of the intracavity polarization controllers, the fluctuations of the pulse peak power could be reduced by 5–7 %. The average output power of the laser was 2.22 mW at a pump power of 43 mW, with a variation of less than 1 dB across the full wavelength sweep. As shown Fig. 2(b), the output
The power of the WSFL was over 1000 times as large as that of amplified spontaneous emission (ASE) of an LD-pumped Er\textsuperscript{3+}-doped fiber (EDF).

2.2. Real-time signal processing scheme

As shown in Fig.1(b), the sensor signals of each sensor arrays are measured with photo detectors. These are wavelength-encoded signals in the time domain as shown in Fig. 3(a). Array 1 has 5 FBG sensors (FBG\textsubscript{1}=1532.58 nm, FBG\textsubscript{2}=1536.36 nm, FBG\textsubscript{3}=1541.40 nm, FBG\textsubscript{4}=1546.26 nm, and FBG\textsubscript{5}=1552.32 nm) and array 2 has 4 FBG sensors (FBG\textsubscript{6}=1536.30 nm, FBG\textsubscript{7}=1541.46 nm, FBG\textsubscript{8}=1546.44 nm, and FBG\textsubscript{9}=1552.38 nm). The number of FBG sensors in one array could be expanded naturally. Electrical signal-processing scheme was utilized to measure the wavelength shift of each sensor. The process is as follows. First, the analog voltage differentiation circuit and zero-crossing comparator execute peak detection of FBG sensors. Second, at the peak point of the sensors, the derivative signal crosses zero voltage and voltage comparator generates a digital pulse signal such as rising edge (from 0 to 5 Volt.) as shown in Fig. 3(b). 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 of 20 MHz and the counted numbers are transferred to the personal computer. By measuring the counted number of
each sensor from the reference sensor and matching the counted number of each sensor to grid counts of the F-P etalon with 1nm interval, the wavelength-shift of each sensor can be calculated. When FBG sensors are in the same environmental temperature and calibrated by temperature compensating reference FBG sensor, the strain is calculated by the following simplified relation between strain and Bragg wavelength shift.

\[
\varepsilon = \frac{1}{(1 - p_e)} \frac{\Delta \lambda_B}{\lambda_B}
\]  

(1)

where \( p_e \) (=0.225) is the photo-elastic constant and measured experimentally\(^7\). Procedures of strain calculation were programmed by Labview software with GUI. The real-time strain monitoring window that displays the strain histories of the FBG sensor could be constructed by this software. The constructed FBG sensor system showed a good strain resolution less than 10 \( \mu \varepsilon \).

![Graphs showing sensor signals and processed signals](image)

Fig. 3  (a) Original sensor signals. (b) Processed signals by electrical circuit.

### 3. VIBRATION SENSING OF A COMPOSITE BEAM

For the verification of the constructed FBG sensor system, impact vibration test was executed with a composite beam. Mode sensing of a structure is generally performed by modal analysis. 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 could get the strain measured mode shape of a structure.

Fig.4 shows the configuration of the composite beam fabricated using graphite/epoxy prepreg. Sensor array 1 and 2 were bonded to the surface of the beam. The locations of FBG sensors were selected to represent the strain based mode shape of a beam correctly. FBG2 is placed such that the second mode of the beam has zero value of strain in that point and FBG6, 8 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 in this experiment, 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 procedures including strain calculation, visualizing and data storage were performed in real-time processing.
Mode shapes of a composite beam can be calculated from the strain histories of nine FBG sensors based on modal analysis. To examine the experimental results, 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. In the frequency domain, all FBG sensors in the beam have the same values of natural frequencies, i.e. 7.72 Hz, 47.85 Hz, 134.12 Hz. As shown in Table 1, the experimental result shows a good agreement with the results analyzed by ABAQUS.
Table 1  Comparison of natural frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Experiment</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>7.72 Hz</td>
<td>7.93 Hz</td>
</tr>
<tr>
<td>2nd</td>
<td>47.85 Hz</td>
<td>49.68 Hz</td>
</tr>
<tr>
<td>3rd</td>
<td>134.12 Hz</td>
<td>139.07 Hz</td>
</tr>
</tbody>
</table>

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

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

4. THE STRAIN MEASUREMENTS OF SMART BRIDGE SPAN

The experiments of strain measurement of scale-down bridge span under concentrated loading were carried out using FBG sensor system. The span of scale-down bridge was made by Plexiglass plate. Fig. 7 shows the schematic and photograph of the experimental setup for the test.
The span of the bridge was clamped at its ends. Four FBG sensors were bonded on the lower part of the span using epoxy. Dimension of the span and bonding locations of FBG sensors are shown in Fig. 8. FBG sensors were connected to one line of optical fiber by an arc fusion splicer. The behavior of the span of the bridge is simultaneously monitored by measuring strains using multiplexed FBG sensor array. The Bragg wavelengths are FBG1 = 1555.6 nm, FBG2 = 1546.1 nm, FBG3 = 1534.7 nm and FBG4 = 1541.5 nm. In order to compare strains measured by FBG sensors with those calculated by a classical beam theory, Young’s modulus, E=3.94 GPa of the acrylic plate was obtained through the tensile test. Experiment was performed by applying the concentrated load at the chosen point of the bridge span using 0.5 Kg mass (4.9 N). Load was applied at the four positions given in Fig. 9. Experimental results are shown in Fig. 10. As shown in the figure, the strains measured by FBG sensors show a good agreement with the strains calculated by a classical beam theory. In particular, the maximum tensile strain is acquired from FBG3 sensor in the case of a/L = 0.5, that is expected by the theory. Since ends of the span are clamped, tensile as well as compressive strains appear along the span. Fig. 11 is a real-time strain measurement window by the signal-processing program. The window could monitor real-timely strain states of the FBG sensors and inform user the dangerous state of the bridge by an alarming sound in the case that monitored strain exceeded a given threshold strain level. The signal process and plotting windows of strains were constructed by use of LabVIEW software. The real-time monitoring window has three parts showing strains and alarms of the bridge span. First, 4 charts of the left side show the strain histories of each 4-FBG sensor when the load of 4.9 N moves discretely along the span of the bridge every 10 cm. In the case of the low strain values for certain sensor, magnified chart by controlling the axis could be utilized. Second chart shows all strain histories of 4-FBG sensors to compare relative strain values of FBG sensors. Third, a visual and audible signal followed by a graphical strain is fully demonstrated. Alarms or warning signals are important part of the management and safety functions of a monitoring system. When the bridge undergoes near the threshold level of strain, FBG sensor system successfully gives early warning sound. The constructed early warning system can be applied to a real bridge structures and give you time to undertake remedial works on bridges before the catastrophic disaster.
$P = 4.9 \text{ N}$

Concentrated load acting points

Fig. 9. Configuration of concentrated load acting points at the span.

Fig. 10  Comparison of strains measured by FBGs and calculated by a classical beam theory.
5. CONCLUSIONS

We constructed an improved FBG sensor system by using WSFL which has high output power. In order to monitor the structural strain real-timely, the signal-processing program and electrical circuit board were constructed using Labview software for storage and visualizing of the data. In the experiment of dynamic strain measurement of a composite laminated beam, the performance of the constructed FBG sensor system was successfully verified. Finally, as a practical application of infrastructure, four FBG sensors in one optical fiber were used to monitor strains of the scale down bridge span. When the strain from FBG sensors of the bridge reaches a critical level of strain, the FBG sensor system tells early warning sound. This early warning system could give you time to undertake remedial works on bridges before the catastrophic disaster. This improved FBG sensor system could be extended to monitor the strains of large-scale infrastructure which requires a large number of sensors.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Science and Technology, Korea, for the financial support by a grant from the Critical Technology 21 project.

REFERENCES