SHAPE ESTIMATION AND HEALTH MONITORING OF A COMPOSITE WIND TURBINE BLADE USING DISTRIBUTED FBG SENSORS

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Abstract

Real-time shape estimation of the composite blade was accomplished using strain data gathered by the arrayed nine fiber Bragg grating (FBG) sensors embedded in carbon spar-caps. The finite element model of the composite blade was created and a displacement-strain transformation based on a modal approach was applied to find the displacement-strain transformation (DST) matrix. The locations of the embedded strain sensors were optimized by minimizing the condition number of the displacement-strain transformation matrix. The modal tests were performed for the experimental validations of shape reconstruction. The estimated shapes measured by embedded Bragg grating sensors are compared with the directly captured deflection shapes derived by high-speed cameras. The results show very close agreement showing the potentials of the proposed shape estimation technique based on displacement-strain transformation using Bragg grating sensors.

1 Introduction

As wind turbines become large, more slender and flexible blades are preferred to reduce aerodynamic loads. Therefore many structural health monitoring technologies have been developed as a method of securing the reliability of these flexible structures during operation [1-2]. As a sensing part of the intelligent structures, fiber optic sensors have shown the potential of the real-time health monitoring system for composite structures. Optical fiber sensors can be easily embedded in composite materials without causing mechanical defects due to the small size and flexibility of optical fibers. In this study, a high-speed FBG interrogator capable of strain monitoring for large wind turbines was developed and applied to the strain based deflection monitoring of a wind turbine blade under dynamic loads.

2 Fiber Bragg grating sensor

2.1 Principle of operation

The FBG has a grating structure in which periodically changing refractive index is engraved in the core of the optical fiber. When a broad-band light enters the grating fiber core, the light defined by the Bragg wavelength, λ_B, expressed with (1) is reflected from the grating, and light of different wavelengths passes through the grating [3].

$$\lambda_B = 2n_e\Lambda \tag{1}$$

$$\varepsilon = \frac{1}{1-p_e}\left(\frac{\Delta\lambda_B}{\lambda_B} - (\alpha+\xi)\Delta T\right) \tag{2}$$

Where, n_e is the effective refractive index of the optical fiber, and Λ is the grating period. When the surrounding part of the FBG sensor is deformed due to external disturbance, such as load or temperature change, which leads to a change in the grating periods of the optical fiber, followed by a change in the Bragg wavelength. The physical quantities, including strain, can be calculated using the change ratio of the reflected wavelength. The strain of a FBG sensor whose photo-elastic constant is P_e can be calculated with (2). Where α is the coefficient of thermal expansion (CTE), ξ is the thermo-optic coefficient.

2.2 Development of FBG interrogator

Figure 1 is a schematic diagram of the high-speed FBG interrogator (KHFI-140) developed in this study [4]. The FBG interrogator was fitted with a spectrometer-type demodulator based on a linear photo detector, implementing a 40 kHz or higher sampling ratio per channel. For highly efficient signal processing, the demodulation of the FBG wavelength signal was carried out using an embedded FPGA. The system was designed with a main control/communication board that saved the demodulated data and exchanged them with the DSP of demodulator and external devices. In the high-speed demodulation mode, up to six arrayed FBGs can conduct 40 kHz sampling per each channel simultaneously, and the system is suitable for structural damage detection by high-frequency vibration sensing such as AE (acoustic emission) detection. In the low-speed demodulation mode, the system can be effectively used for the dynamic strain monitoring of large structures that require many sensors, by expansion of the sensing channels.

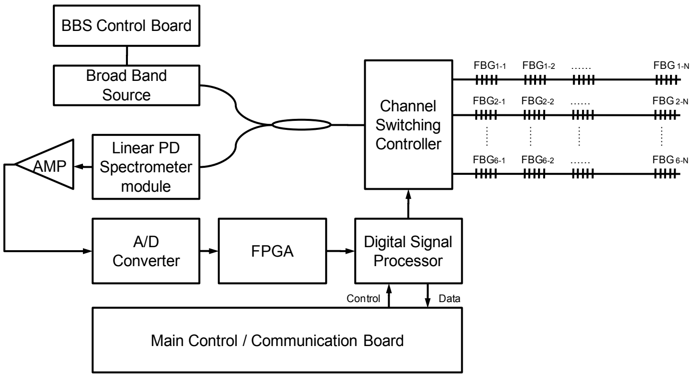


Figure 1. Schematic diagram of high-speed FBG interrogator

3 Strain based shape estimation

3.1 A modal approach

The structure displacements $\{y\}$ can be estimated as the multiplication of the structure strains $\{\varepsilon\}$ and adequate displacement-strain transformation (DST) matrix $[T]$ as in equation (3) [5,6].

$$\{y\}_{N\times 1} = [T]_{N\times M}\{\varepsilon\}_{M\times 1} \tag{3}$$

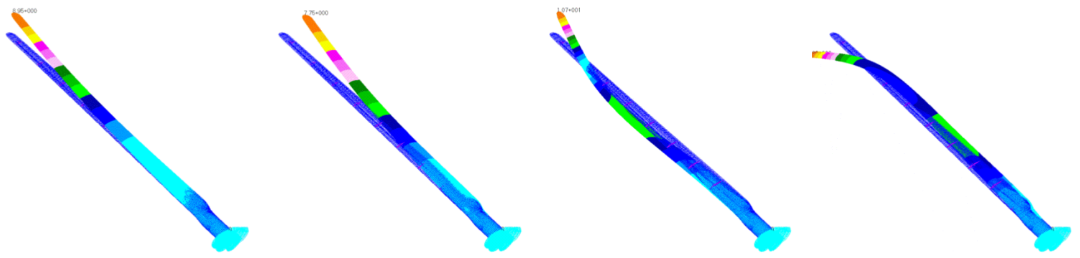
DST matrix [T] is expressed in terms of the strain mode shape matrix [Ψ] and the mode shape matrix [Φ] as follows:

$$[T]_{N\times M} = [\Phi]_{N\times n}\cdot([\Psi]_{n\times M}^{T}\cdot[\Psi]_{M\times n})^{-1}\cdot[\Psi]_{n\times M}^{T} \tag{4}$$

Where N is the number of displacements, n is the number of used modes, and M is the number of measured strains. Usually, the condition number (CN) can be used as a quality measure of the DST matrix. A smaller condition number is desirable for a more accurate shape estimation of the structure, so the sensor locations can be optimized by performing the CN minimization [6, 7].

3.2 Modal analysis of a wind turbine blade for DST matrix formulation

The finite element model of the composite wind turbine blade was created and the displacement-strain transformation (DST) matrix on the basis of the modal approach was obtained. The blade was modeled in MSC Patran™ and it was modeled using QUAD4 and TRI3 shell elements. This 11m-length blade model was composed of 6,848 elements with 6,655 nodes and the root section was constrained as a cantilever.

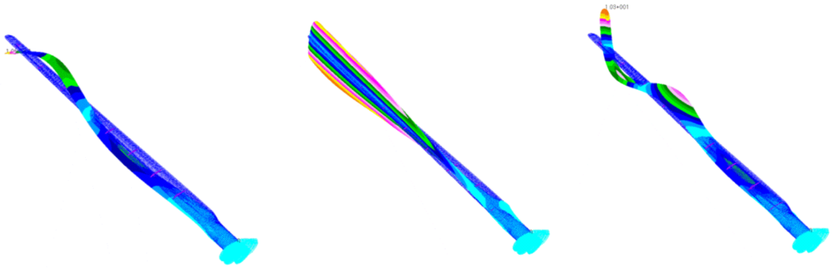


(a) Mode 1: 2.76Hz
1st flapwise

(b) Mode 2: 5.46Hz
1st edgewise

(c) Mode 3: 9.15Hz
2nd flapwise

(d) Mode 4: 18.61Hz
2nd edgewise



(e) Mode 5: 20.85Hz
3rd flapwise

(f) Mode 6: 29.01Hz
1st torsion

(g) Mode 7: 34.8Hz
4th flapwise

Figure 2. Mode shapes and frequencies of the composite wind turbine blade

Figure 2 present the results of the modal analysis of the composite blade. The result of the FEA shows that the first resonance frequency is 2.76 Hz and the shape of the vibration mode is the first bending mode in flapwise direction. The second resonance frequency is 5.46 Hz, and the mode shape is the bending mode in edgewise direction. The 3rd vibration mode shows 9.15 Hz of natural frequency. Mode 6 is the first twist mode. In the natural frequency in higher modes, complex mode shapes mixed with various vibration modes including twist was observed.

4 Measurement of strain based bending deflection of a wind turbine blade using arrayed FBG sensors

4.1 Test setup

In this study, the deflection-monitoring test of the 11m span composite blade was conducted to verify the applicability of the FBG sensors in shape estimation under dynamic loading. Figure 3 shows the experimental apparatus. The composite wind turbine blade was made by resin infusion molding process. During the manufacturing, an arrayed 9 FBG sensors were embedded in the selected locations of blade skin. The fiber optic cable from the FBG array was connected to the KHFI-140 FBG interrogator through an ingress/egress port on the inner surface of the blade root. On the blade surface, 33 reflecting markers for stereo pattern recognition (SPR) were bonded and 8 high-speed cameras for SPR system were installed for the comparison of the measured deformation. On the dynamic loading test, snapback load with initial 100mm deflection was applied to the flapwise direction on the 95% blade span location.

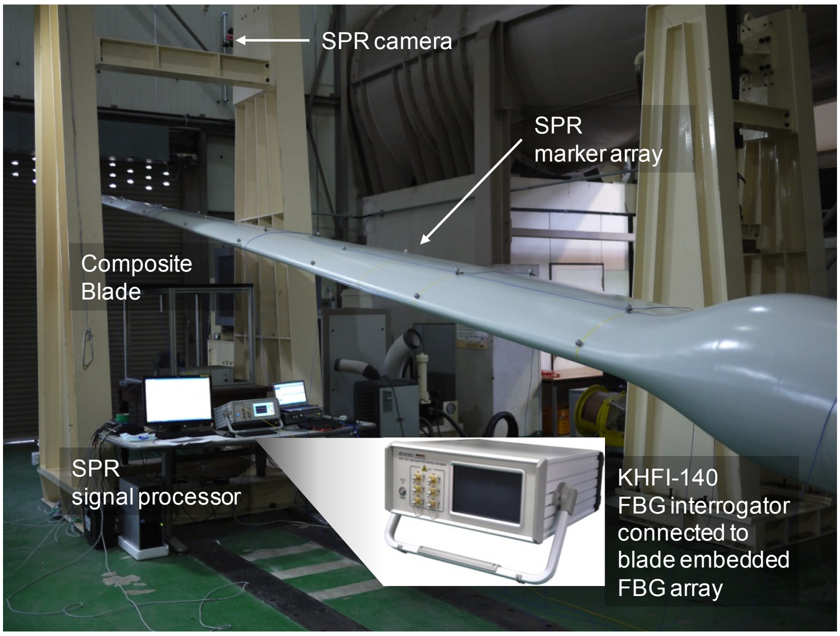


Figure 3. Experimental setup for blade deflection measurement test

4.2 Experimental results

Figure 4 shows the strain monitoring results measured by arrayed 9 FBG sensors. In snapback region, static deflection load was applied inducing the maximum 246 $\mu\varepsilon$ in FBG4. After releasing the blade at 4.9 sec, impulsive load inducing the dynamic deformation of the blade was generated. Under the release condition, the measured strain on the root region shows relative higher level than those of tip area and the shape of the blade is mainly composed of the vibration mode 1. From the power spectrum of the strain data, we could observe the lower 5 vibration modes including 3 flapwise bending modes with 2 edgewise bending modes. However, in snapback vibration excitation test, the torsional modes are hardly visible. Thus, the mode 6 was excluded from the set of relevant modes used for the formulation of the DST matrix. Finally, the DST matrix of [33 by 9] size was formulated for the shape estimation of the 33 marker locations on blade upper skin.

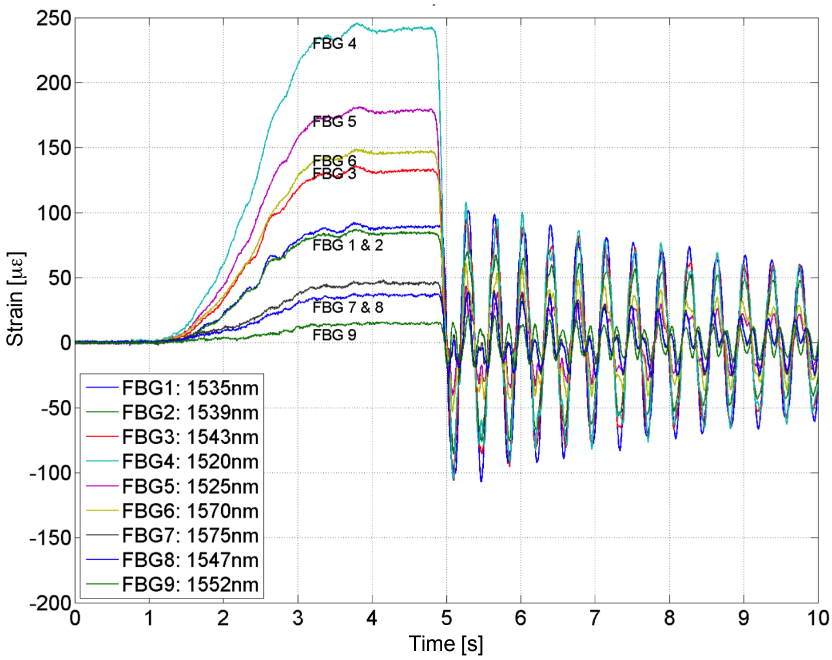


Figure 4. Measured strain data by arrayed FBG sensors on snapback excitation of 95% blade span location

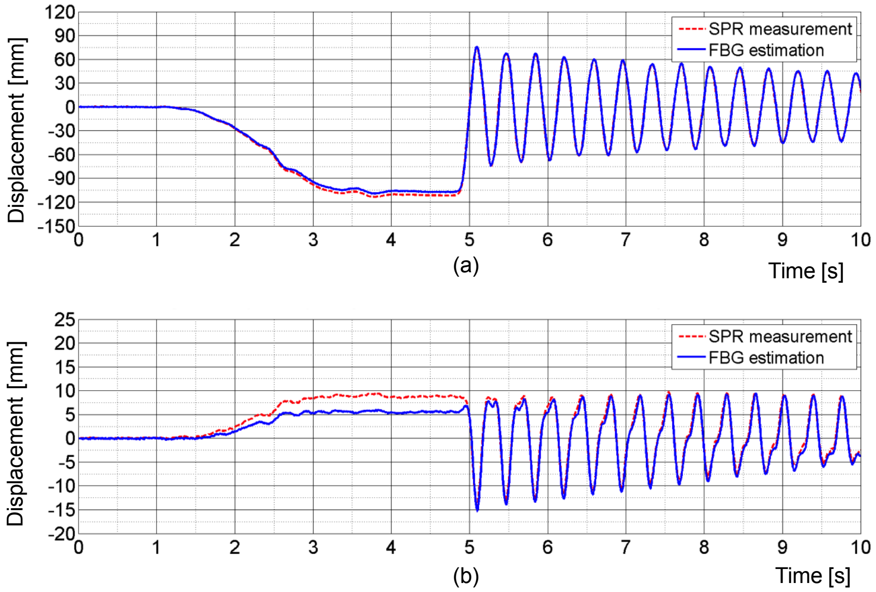


Figure 5. Estimated (a) flapwise and (b) edgewise displacement by FBG sensors with DST matrix in blade tip location

Figure 5 (a) and (b) show the transformed displacement in blade tip measured by FBG sensors with DST matrix. In the figures, transformed displacements from the arrayed FBG sensors are expressed in solid lines while the measured deflections by SPR cameras are shown in dashed lines. From the figures, it can be observed that the blade bent about 106.3mm toward the downward flapwise direction when the static flapback load was applied. After releasing the blade, the amplitude of the flapwise vibration gradually decreased from the maximum 75.8mm deflection. Even though, there are small discrepancies of the edgewise deflections on the static loading region, the overall error was order of millimeter. From the results, both flapwise and edgewise displacements estimated by DST matrix with FBG measured strains were well matched with the results from SPR cameras. Figure 6 shows the comparison of reconstructed deformed shapes of the blade using the deformations of 33 marker points transformed by DST matrix.

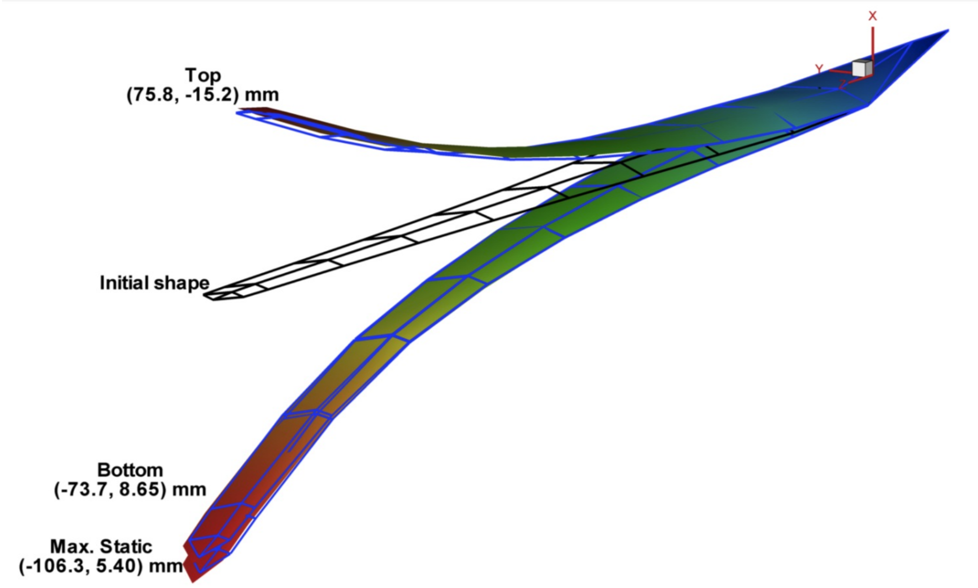


Figure 6. Comparison of the blade deflection shapes measured by FBG sensors using DST transform with the surface contour measured by SPR

4 Conclusion

In this study, a high-speed FBG interrogator was used for the strain-based deflection shape estimation of composite wind turbine blade. FEM based strain-displacement transformation process was developed for the shape estimation of the complex structures using arrayed FBG sensors. For the deflection shape estimation using modal approach, FE analysis of composite blade was done to formulate the DST matrix. To verify the applicability of the FBG sensors in shape estimation under dynamic loading, the flapback deflection monitoring test of the blade was conducted and the results were compared with the SPR measured deflections. From the series of experiments, it is clear that out-of-plane deflections can be nicely estimated by the arrayed FBG sensors and the possibilities of optical fiber sensors in structural shape monitoring was confirmed.

Acknowledgments

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References

[1] McMillan D., and Ault G. Condition monitoring benefit for onshore wind turbines sensitivity to operational parameters. *Renewable Power Generation*, **vol. 2, no.1**, pp. 60-72 (2009).

[2] Ciang, C. C., Lee, J. R., and Bang, H. J. Structural health monitoring for a wind turbine system: a review of damage detection methods. *Meas. Sci. Technol.,* **vol. 19**, pp1-20 (2008).
[3] Udd, E., and Spillman W. J., "Fiber Optic Sensors", John Wiley and Sons, New York, pp.325-365 (1991).
[4] Bang H. J., Jang M. S., and Shin H. K. *Structural health monitoring of wind turbines using fiber Bragg grating based sensing system* in Proceeding of *Smart Structures and NDE; SPIE 7981*, San Diego, U.S. (2011).
[5] Kang L. H., Kim D. K., and Han J. H. Estimation of dynamic structural displacements using fiber Bragg grating strain sensors. *Jour. of Sound Vib*., **vol. 305**, pp.534–42 (2007).
[6] Rapp S., Kang L. H, Han J. H., Mueller U. C., and Baier H. Displacement field estimation for a two-dimensional structure using fiber Bragg grating sensors. *Smart Mater. Struct.,* **vol. 18**, pp.025006 (2009).
[7] Li C. J. and Ulsoy A. G. High-precision measurement of tool-tip displacement using strain gauges in precision flexible line boring. *Mechanical Systems and Signal Processing*, **vol.13, no.4**, pp.531-46 (1999).