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ONLINE NON-CONTACT TORSION SENSING METHOD USING FIBER BRAGG GRATING SENSORS AND OPTICAL COUPLING METHOD

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Abstract

Online measurement of torsion of a rotating shaft has been dominantly conducted by strain-gages combined with either a slip ring or telemetry. However, both methods have severe inherent problems like low S/N ratio, high cost, and difficult installation. FBG (Fiber Bragg Grating) sensor can measure both strain and temperature. It has much superior characteristics compared to strain-gages and has been used in various mechanical engineering applications in recent years. In this paper, a new method using FBG sensors for online non-contact torque monitoring is suggested. This system uses optical coupling to connect FBG sensors on the rotating shaft to instruments at stationary side. A reference FBG sensor on the shaft has been also introduced to compensate the insertion loss change due to rotation. A single optical fiber with three FBG sensors (two for torsion measurement and one for compensation) is installed on the shaft and all instruments are installed at stationary side thereby giving tremendous advantages over a slip ring or telemetry. The suggested system's superior performance potential is demonstrated with experiments.

1. INTRODUCTION

Rotating parts like blades of a helicopter or a turbine are common and mostly critical elements of a mechanical system. So online condition monitoring of these critical rotating parts is very important to prevent unexpected catastrophic failures and save maintenance cost. It is usually much better to install sensors like strain-gages on the rotor and measure the signal directly rather than measuring indirect signals like acceleration on bearing housing to monitor rotor condition. However, it is very difficult to make the physical connection between sensors on the rotor and instruments on the stationary side. Use of strain-gages combined with either a slip ring or telemetry has been the dominant method to measure strain at various points of a rotor. But both slip ring and telemetry have severe inherent problems like low S/N ratio, high cost, limited number of channels, RPM limitation, very difficult installation, etc. [1].

FBG (Fiber Bragg Grating) sensor can measure both strain and temperature and has

characteristics much better than strain-gage's [2]. FBG sensors have been mostly used to monitor large civil structures like bridges or tunnels and begun to be used in mechanical applications in recent years. With the recent rapid growth of wind turbine industry, FBG sensors have been also applied to monitoring the condition of blades whose size have grown more than 60 meters. Optical fibers which have many FBG sensor points were installed on the wind turbine blades to monitor stress and temperature and to detect cracks [3, 4]. However, in those researches, signal processing instruments were installed inside rotor hubs and telemetries were used to send the data to ground stations.

In this paper, a new online torque measuring method using FBG sensors which does not require telemetry is explained. This revolutionary system uses optical coupling to connect the sensor signal to the instrument at stationary side and uses a reference FBG sensor installed at the shaft to compensate the inevitable insertion loss change due to rotation. A single optical fiber with three FBG sensors (two for torsion measurement and one for compensation) is installed at the shaft and unlike the wind turbine case, the dynamic optical interrogator is installed at stationary side. The optical coupling gives tremendous advantages over a slip ring and telemetry. There have been several research works which have used FBG sensors with various optical coupling methods. Temperature of rotating shaft was measured using a FBG sensor on a shaft and optical coupling. But the temperature could be measured only once per revolution and continuous online monitoring could not be obtained with that set-up [5]. Combination of FBG sensors and optical coupling was also used to measure torque of a shaft, however, the result shows there is severe signal distortion caused by insertion loss change due to rotation. Solution to reduce this distortion has not been suggested and it has only shown the possibility that torque could be measured with optical coupling [6]. In this paper, the torque of a shaft is monitored online while the insertion loss change due to rotation is being compensated. The suggested system's superior performance is demonstrated with experiment.

2. SYSTEM DESCRIPTION

Figure 1 shows the concept of proposed torsion sensing set-up. Two torsion sensing FBG sensors, $\mathbf{S_1}$, $\mathbf{S_2}$, with different center wavelengths are mounted to the shaft at 45 ° with respect to its axial direction. One FBG reference sensor, **R**, is installed axially inside a shaft. One C-lens is mounted axially at shaft end and another C-lens is installed at the stationary side. These two C-lenses are used for cullimination and focusing purposes to expand cross-section area of light travel pass. In this set-up, broadband light source from the dynamic interrogator reaches right C-lens. Then, the C-lens expands the cross section of the light travelling pass by cullimination. The light crosses the space between two C-lenses and is focused to the optical cable by left C-lens. Light reflected from each FBG sensor crosses the space back to the interrogator using the same procedure. This optical coupling method insures continuous light connection when the shaft is rotating.

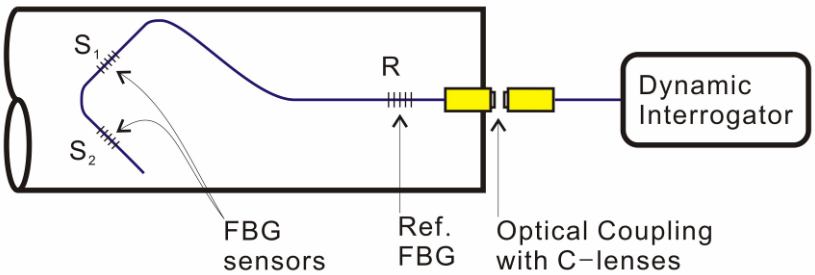

Figure 1. Torsion sensing set-up using FBG sensors and optical coupling

In this optical coupling method, there is always inevitable insertion loss when light travels between the space and the magnitude of this insertion loss is changed with shaft rotation. So this insertion loss change due to rotation has to be compensated to get accurate measurement. To solve this problem, it is assumed the insertion loss change due to rotation is same for all FBG sensors on the rotating side. So one reference sensor is purposely installed at the axial center line where the centrifugal force is minimum. Theoretically the signal from the reference sensor should represent only the insertion loss change and the torsion sensing FBG sensor signal have both torsion measurement and insertion loss change. So by taking the difference of the reference sensor signal and torsion sensing sensor signal, torsion signal can be accurately measured.

The torsion of a shaft can be calculated as follows using Figure 2. In the Figure, r, T and τ are radius of the shaft, applied torque and applied shear stress respectively. $\varepsilon_1 = -\varepsilon_2$ is the normal strain along a line oriented with respect to the shaft axis by angle 45° and ε is the mean of ε_1 and $-\varepsilon_2$.

$$\tau = \frac{T \cdot r}{J} \tag{1}$$

$$\varepsilon = \frac{\varepsilon_1 - \varepsilon_2}{2} = \tau \frac{\tau}{E} \cdot (1+\nu) \tag{2}$$

In equation (1), J is the polar moment of inertia of the cross-section and is $\frac{\pi \cdot r^4}{2}$ for a solid circular shaft. E is Young's modulus and ν is Poisson's ratio of shaft material. Torque can be calculated by equation (3).

$$T = \frac{(\varepsilon_1 - \varepsilon_2) \cdot E \cdot J}{2r \cdot (1+\nu)} \tag{3}$$

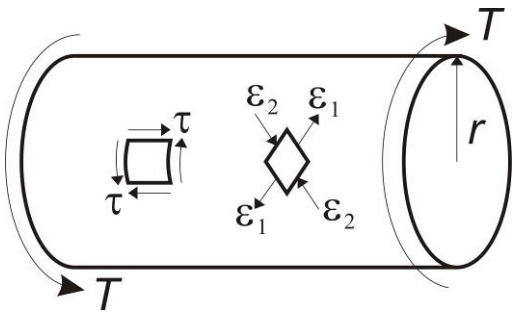

Figure 2. Torsion sensing method

3. EXPERIMENTAL SET-UP

Experimental set-up is shown in Figure 3. An AC servo motor at the left side drives the shaft using a gear type reducer. A torque meter is installed to verify measurement by FBG sensors and a magnetic brake at the rear is used to give resistance to the rotation thereby giving torque to the shaft. Two FBG sensors were installed to the shaft as described in section 2 and one FBG reference sensor is installed at the center line of the shaft to minimize the effect of centrifugal force. The reference sensor is also treated with special package to make the sensor signal insensitive to any vibration from environment. The wavelength reflection characteristics of

these three FBG sensors are shown in Figure 4. In the figure, the left-most peak is of the reference sensor and the other two peaks are of the torsion sensing FBG sensors. Their peak wavelengths are 1531, 1554, and 1563 nm respectively.

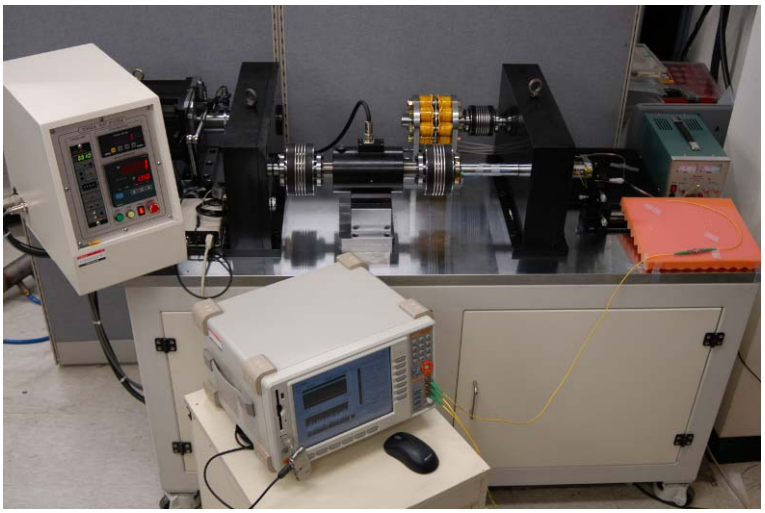

Figure 3. Experimental set-up

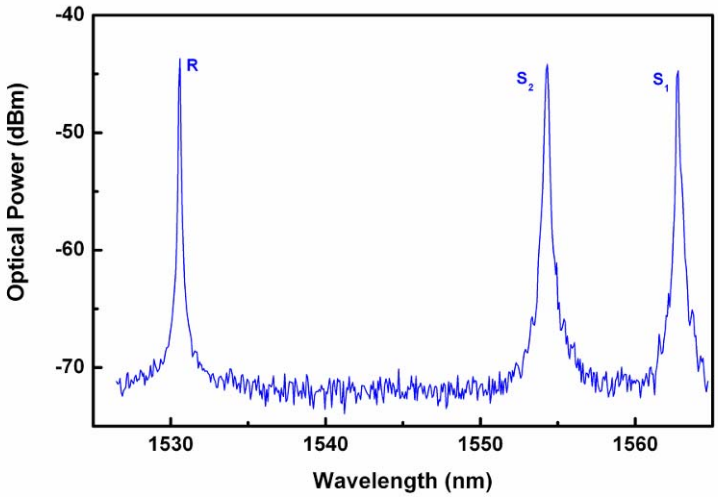

Figure 4. Characteristic center wavelengths of three FBG sensors

Optical coupler is at the right side in the Figure 3 and close-up view is in Figure 5. At the shaft end, two rotation axes adjustment mechanism using bolts is installed for the alignment of the C-lens. The C-lens at the stationary side is installed on a five axes adjustment mechanism. In-house developed dynamic optical interrogator is used for signal processing. It uses frequency domain modulation method and unlike static methods, it assigns a turnable filter to each FBG sensor signal for fast signal processing. It has 14 channels and the current maximum sampling speed is 8 kHz for each channel.

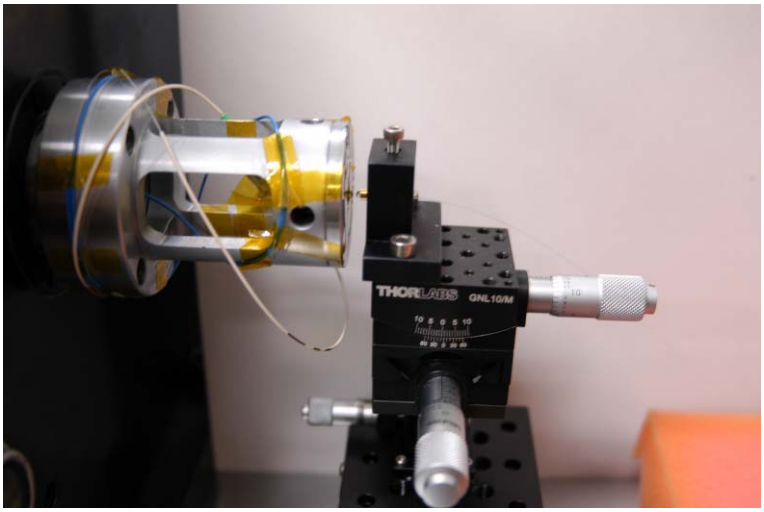

Figure 5. Optical coupler

4. RESULTS AND DISCUSSION

4.1 Insertion Loss Change Compensation

Figure 6 shows the compensation example when the shaft is rotating with the magnetic brake off. Figure a), b) show insertion loss changes of reference and torque sensor respectively during rotation. As expected, both signal show very similar shape verifying author's assumption that the insertion loss change due to rotation is same for all FBG sensors. The compensation result by taking the difference of these two signals is shown in figure c).

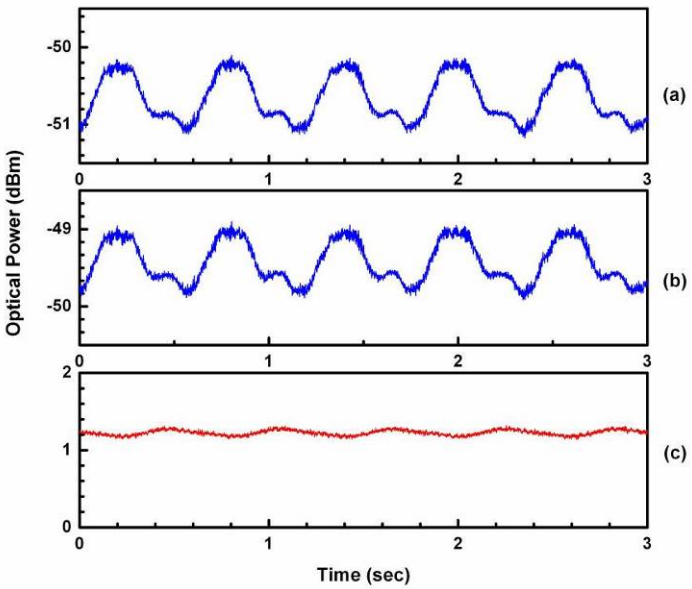

Figure 6. Compensation result of insertion loss change due to rotation: a) reference sensor signal, b) torsion sensing FBG sensor signal, c) signal after compensation

4.1 Torque Measurement Result

Figure 7 shows the comparison of torque measurement by torque meter and proposed method. Torque measurements were taken while the magnetic brake force was varied. The result shows the proposed method is working with very good accuracy.

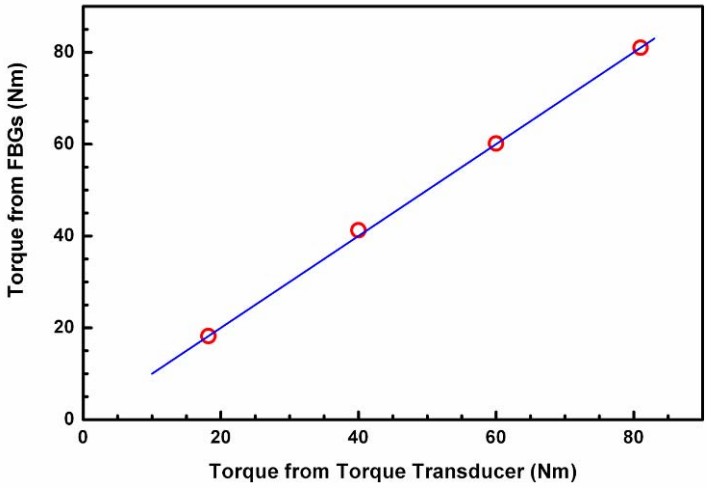

Figure 7. Measurement comparison between torque meter and FBG sensor.

5. CONCLUSIONS

A new torque monitoring system using FBG sensors and optical coupling is proposed. Unlike commonly used strain gage method, this system does not require either the slip ring or telemetry. Only one optical fiber with three FBG sensors is installed at the shaft and all instruments are installed at stationary side. The signal connection between rotating part and stationary part is made by optical coupling thereby giving tremendous advantages over strain-gage method. In optical coupling, there is inevitable insertion loss and this loss is changed with rotation. To solve this problem, a reference sensor is successfully introduced to compensate this insertion loss change due to rotation. The proposed system's performance potential is demonstrated with experiment. The result shows this revolutionary new method can be used for online torsion monitoring overcoming numerous limitations of conventional monitoring methods using strain gages combined with either a slip ring or telemetry.

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