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A NEW ONLINE ROTOR CONDITION MONITORING METHOD USING FBG SENSORS AND NO TELEMETRY SYSTEM

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Abstract

Online stress monitoring at various points on a rotor has always been a challenging issue especially under critical conditions. Strain-gages combined with a slip ring or a telemetry system have been dominantly used to measure stress of a rotor and FBG (Fiber Bragg Grating) sensors combined with a telemetry system also have been recently used especially in wind turbine blade monitoring. FBG sensor generally has much superior characteristics compared to strain-gage's, however, currently it needs a telemetry system to be used for rotor condition monitoring to send measured data to the ground station. In this paper, a new FBG sensor system for rotor condition monitoring which does not require a telemetry system is explained. This revolutionary system makes use of light's unique characteristic - light travels through space. A single optical fiber with many FBG sensors is installed on the rotor and unlike other systems all necessary instruments are installed at stationary part thereby giving tremendous advantages over a slip ring or a telemetry system. The suggested system's superior performance is demonstrated with experiments.

INTRODUCTION

Rotating parts like blades of a helicopter or a turbine are common and mostly critical parts of a mechanical system. So online condition monitoring of these 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 part. Strain-gages combined with either a slip ring or a telemetry system have been the dominant method to measure the stress of a rotor. But these connections have many inherent problems like low S/N ratio, high cost, limited number of channels, etc. [1].

FBG (Fiber Bragg Grating) sensor can measure both stress and temperature and has characteristics much better than strain-gage's. FBG sensors have been mostly used to monitor large civil structures like bridges or tunnels. With the recent rapid growth of wind turbine industry, FBG sensors have been also researched to monitor the condition of blade whose size has 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 detect cracks [2, 3]. However, in those researches, all sensor systems were installed inside rotor hubs and telemetry systems were used to send the data to ground stations.

In this paper, a new rotor condition monitoring system using FBG sensors which does not require a telemetry system is explained. This revolutionary system makes use of light's unique characteristic - light travels through space. A single optical fiber with many FBG sensors is installed on the rotor and sensor system is installed at stationary side. The connection between rotating part and stationary part is made by light thereby giving tremendous advantages over a slip ring and a telemetry system. There have been several research works which have used FBG sensor with light connection. Temperature of rotating shaft was measured by a FBG sensor on a shaft and light connection. But the temperature could be measured only once per revolution and continuous online monitoring was impossible [4]. FBG sensors and light connection were also used to measure torque of a shaft, however, the result shows there is severe signal distortion caused mainly by light transmission loss change due to rotation. Solution to reduce this distortion was not suggested so it has only shown the possibility that torque could be measured with light connection [5]. In this paper, the stress of many FBG sensor points on a rotor is monitored online while the light transmission loss by rotation is eliminated. The suggested system's superior performance is demonstrated with experiments.

FBG SENSOR SYSTEM

Fig. 1 shows the principle of FBG sensor [6]. One section of an optical fiber is processed to have a periodic modulation of index of refraction through grating process. This grated part is called FBG sensor and reflects light with a specific wavelength. So when a broadband light is fed to the optical fiber, light with a certain wavelength is reflected at the FBG sensor to the light source side as shown in the figure. If stress either compression or tension is applied to the FBG sensor, the wavelength of the reflected light is changed. So the stress change can be monitored by observing this wavelength change. A single optical fiber can has many FBG sensors which have different wavelength reflection characteristics.

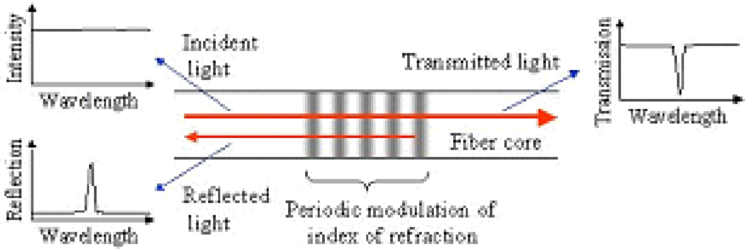


Figure 1 - Principle of FBG sensor

The wavelength change is proportional to the change of temperature and stress as expressed in the equation below. In this paper, temperature is assumed to be constant and only the wavelength change due to stress change has been explored. For a typical optical fiber there is a 1.2 pm shift in the center wavelength of the grating as a result of applying 1 $\mu\varepsilon$. And a shift in the wavelength due to thermal change is 11pm/℃.

$$\Delta\lambda = \alpha\Delta\varepsilon + \beta\Delta T \tag{1}$$

where $\Delta\lambda$, α, β, ε, T are wavelength shift, strain sensitivity (1.2pm/µ), temperature sensitivity (11pm/℃), strain, and temperature respectively.

Conventional FBG sensor system is shown in Fig. 2. Broadband light is fed to the FBG sensor and the light reflected at the FBG sensor is connected to a tunable filter through optical circulator. The tunable filter transforms the change of wavelength into change of light intensity. This light intensity change is also transformed into voltage change by a photo diode. This voltage signal is sampled by A/D converter and stress change is calculated by computer.

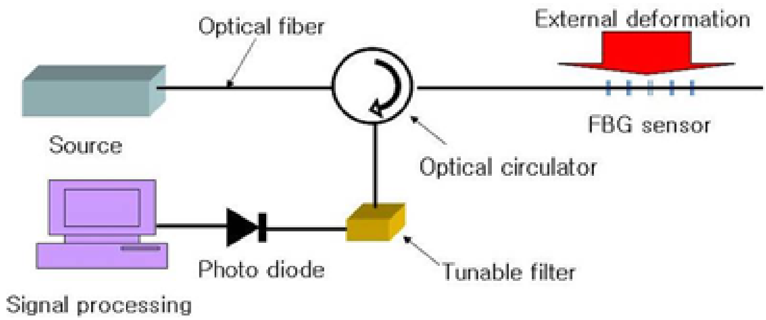


Figure 2 - FBG sensor system

A single optical fiber can have many FBG sensors. In this case, each FBG sensor needs its own tunable filter and photo diode. Each tunable filter has to be carefully adjusted for each wavelength associated with the specific FBG sensor.

PROPOSED CONCEPT

Fig. 3 shows proposed new FBG sensor system with light connection through air gap. The optical fiber in Fig. 2 is now divided into two parts between optical circulator and FBG sensor. The connection between two divided fibers is made by light using its unique characteristic – light travels through space. The FBG sensor on the right side represents a sensor on a rotating rotor and all other instruments are at the stationary side.

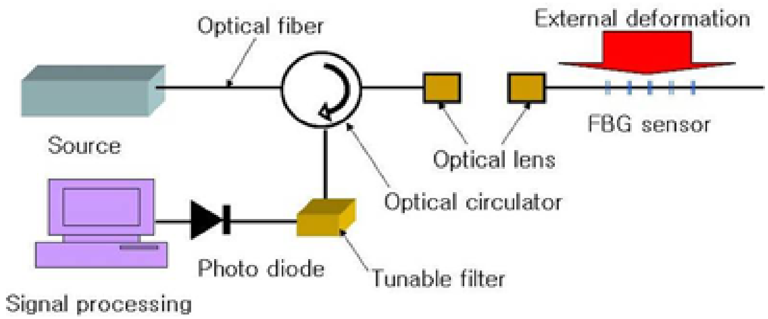


Figure 3 - Proposed FBG sensor system using light connection

Fig. 4 shows the proposed concept of monitoring rotor stress using FBG sensors. An optical fiber with many FBG sensors is installed on a rotor. Each FBG sensor is firmly fixed to the rotor surface. One end of the optical fiber on the rotor is located at the center of the shaft and at the opposite side which is stationary part, one end of another optical fiber is located at the same axis direction. The left optical fiber is connected to the sensor system which includes a light source, light processing units and a computer. Broadband light is emitted from a light source and connected to the left optical lens by optical circulator as in Fig. 3. The light emitted from the left optical lens crosses the gap between two lenses and eventually reaches the FBG sensors. Each light reflected from the sensor reaches the right optical lens and moves back to the left optical lens and is connected to the sensor system for stress calculation. The role of those optical lenses is to keep the optical connection not to be broken while the rotor is rotating. The diameter of the optical fiber core is very small (15 μ-meter for example) and there are mechanical alignment errors, optical errors, and rotor vibration so the light connection can be easily broken. To prevent this problem, optical lens is used at the end of each optical fiber. The optical lenses are used for collimation and focusing to make the cross-section of light connection wider. When light is emitted from the end of optical fiber where one end of the lens is attached, this lens makes the light to be emitted parallel to the shaft at the other end with much larger surface area. When the light crosses the gap and reaches the other lens, the optical lens makes the light to be focused to the optical fiber. So the optical connection between two optical lenses can be sustained even the rotor is rotating. Either graded index (GRIN)-rod lens or C-lens could be used as optical lens.

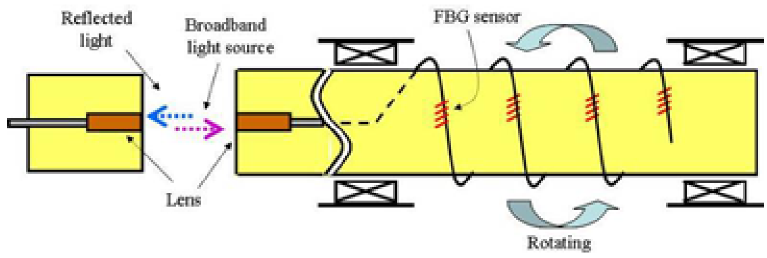
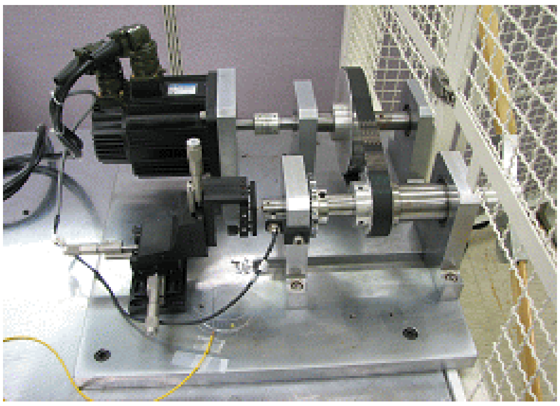
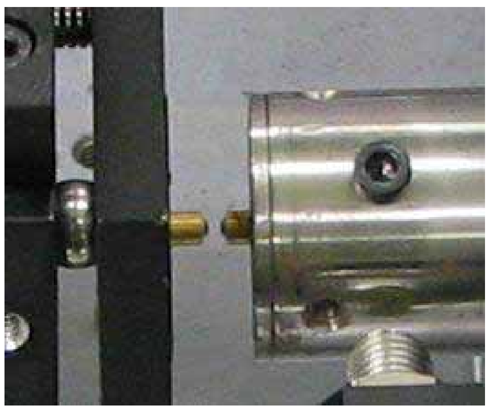


Figure 4 – Proposed rotor stress monitoring method with FBG sensors and light connection

PRELIMINARY EXPERIMENT

Fig. 5(a) shows experimental setup for the proposed rotor stress monitoring method. A servo motor rotates a shaft which is connected to a second shaft by a rubber belt. Two blades at the right side are connected to the second shaft. Ten FBG sensors are used and each blade has five FBG sensors fixed to its surface along center line. Sensor system (not shown) is at the left side and Fig. 5(b) shows close-up view of the proposed light connection using C-lenses. In Fig. 5(b) the shaft at the right side is rotating and the left side is stationary part. So the broadband light source crosses the gap from left to right and each reflected light with a specific wavelength crosses the gap from right to left and processed by a sensor system.





(a) overview *(b) close-up of light connection*

Figure 5 - Experimental setup for the proposed rotor stress monitoring

Fig. 6 shows one example of sensor signals from all ten FBG sensors while the blades are rotating. It shows that proposed light connection method is working. However, close examination has revealed the signals are severely distorted. As shown in Fig. 6 the magnitude of all ten sensors' signal changes simultaneously and the change is periodic with time. This means the distortion is related to shaft rotation. In the next section, the cause of this signal distortion, correction method and corrected result are explained.

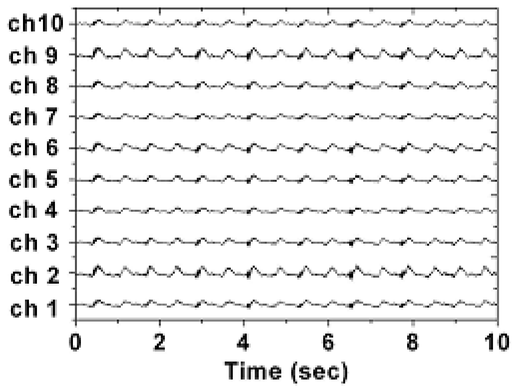


Figure 6 - Signals from ten FBG sensors on the blades

COMPENSATION OF LIGHT TRANSMISSION LOSS CHANGE DUE TO ROTATION

When light travels between two optical lenses, there is always inherent transmission loss which is a very important factor in the proposed system. And it turned out that the magnitude of light transmission loss is also severely changing with shaft rotation. This change is caused by mechanical and optical errors. In the experimental setup, two optical lenses have to be very carefully aligned to minimize alignment error, however, very small alignment error is always inevitable and the optical lenses are also not perfect to make light parallel to axis line. All these reasons attribute to the light transmission loss change with the rotation of the rotor. Fig. 7 shows one example of the measured light transmission loss change due to rotation.

It was found that the magnitude of this light transmission loss change is significantly larger than the magnitude of stress change, so this change due to rotation has to be compensated. A reference sensor is used for this purpose. Unlike other sensors which measure the stress, the reference sensor has to measure only the light transmission loss change and should be free from any stress change. So the reference sensor which is also a FBG sensor is installed right before the optical lens at the end of rotor. By installing the reference sensor at center line, the sensor has minimal effect from rotation thereby sensing almost little of centrifugal force. The light transmission loss should be common to all FBG sensors including the reference sensor. So by subtracting reference sensor signal from other FBG sensors' signals, the exact stress change at each sensor point can be accurately estimated while the rotor is rotating.

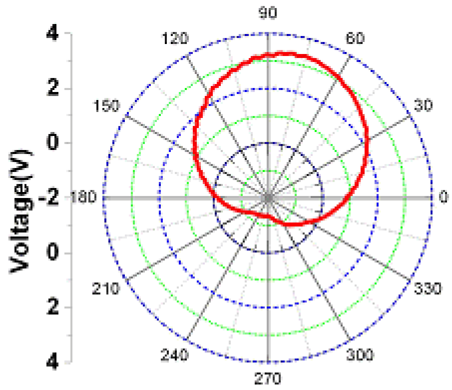


Figure 7 - The variation of light intensity caused by blade rotation

Fig. 8 shows the initial and compensated stress signals of the blade. While the blade is rotating slowly, an impact is intentionally given to the blade. The top graph is the signal from one of the FBG sensor on the blade. It shows large fluctuating signal by light transmission loss change due to rotation and transient stress change due to impact. Center graph shows light transmission loss change measured by the reference sensor. Although the reference sensor should be shielded from any stress change, the center graph shows the reference sensor also sensed the shock because of poor isolation in the experiment. The bottom graph shows the impact stress change after compensation. This result is from preliminary experiment with poor refinement of sensors and instruments so the signals are not in good condition, however, it clearly shows the stress on a rotor can be monitored online with the suggested new method.

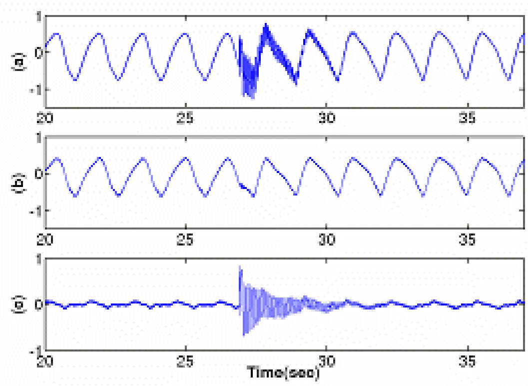


Figure 8 - Elimination of the rotation error: (a) FBG data from blade, (b) reference FBG sensor data, (c) impact signal after compensation.

CONCLUSIONS

A new rotor stress monitoring system using FBG sensors and light connection is proposed. In this system, only one optical fiber with many FBG sensors is installed on a rotor and all instruments are installed at stationary side. The connection between rotating part and stationary part is made by light thereby giving tremendous advantages over strain-gages with a slip ring or a telemetry system. In this light connection, shaft rotation causes the magnitude of light transmission loss changes with rotation angle change. A reference sensor is introduced for the compensation of this light transmission loss change due to rotation. The proposed system’s superior performance is demonstrated with actual experiment with rotating blades. The result shows this revolutionary new method can be used for online rotor stress monitoring overcoming numerous limitations of conventional rotor condition monitoring methods.

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