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Fiber Optical Grating Sensors for Railroad Applications

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Summary

Through experimental testing, the University of Illinois at Urbana-Champaign (UIUC) demonstrated that fiber-optical sensors have superior performance in terms of higher sensitivity and less noise than electrical strain gage sensors. Fiber-optical sensors play an important role in applications for monitoring the health of civil infrastructures such as bridges, oil rigs, and railroads. The potential railway applications for fiber-optical sensors include trackside vehicle performance measurement systems. They are immune to electromagnetic noise (e.g., lightning), less prone to weather damage, and have less static noise. In addition, multiple sensors can be integrated into a single optical fiber and thus achieve simultaneous measurements of strains at multiple locations on the same rail. The high precision response of fiber-optical sensor systems makes them an ideal candidate for train velocity measurements, wheel impact monitoring, derailment prediction, and causal analysis of accidents.

Experimental testing was completed to obtain fiber optical strain sensors for railroad applications. The test setup consisted of sensors (fiber optic and strain gages) applied to a segment of rail. The rail was supported on crossties and loaded with vertical and lateral actuators. The fiber-optical sensor designed by UIUC has been extended to accommodate multiple sensors with negligible crosstalk. In the lab, the fiber optical grating sensors are more sensitive than strain gages. Results show that two fiber-Bragg grating (FBG) sensors can detect 1 ton of vertical load with a square wave pattern and 0.1 ton of lateral load (3 tons and 0.5 ton, respectively, for strain gages). Moreover, research shows that a single fiber grating strain sensor can detect and distinguish simultaneous lateral and normal loads applied at different frequencies.

The fiber optic sensors show good location sensitivity, as well. When two cascaded FBG sensors on a rail track section are tested, the optical response of the sensor 7 inches away from the position of applied force decays to one third of the response of the sensor at the location of the applied force. This feature makes the sensors useful for sensing spatial and temporal events, such as truck hunting, using a single fiber cable on each rail.

The experimental setup consists of a low cost FBG sensor system with a distributed feedback laser as the light source and optical components such as optical isolators and filters. A square wave was applied in the vertical direction and saw-tooth waveforms were applied in the lateral direction with varying frequencies. The sensor output was obtained for a vertical load of 0.3 ton at 1 Hz square waveform and compared it to those with the addition of a lateral load of 0.2 ton at 0.3 Hz and 0.4 Hz saw-tooth waveforms.

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INTRODUCTION

Fiber-optical sensors have been employed in many ways for monitoring the health of civil infrastructure such as railroads, oil rigs, and bridges. With the reduction in cost for fiber-optical systems, fiber-optical sensors have become more feasible and desirable for practical applications for their ease of integration and superior performance over their electrical counterparts. They are immune to electromagnetic noise, less prone to weather damage, and have less static noise. In addition, multiple sensors can be integrated into a single optical fiber and thus achieve simultaneous measurements of strains at multiple locations on the same rail. The high precision response of fiber-optical sensor systems makes them an ideal candidate for train velocity measurements, wheel impact monitoring, derailment prediction, and causal analysis of accidents. They can also be extended to other applications such as passenger or load estimations and time-of-arrival estimations.

OBJECTIVE

Experimental testing was completed to obtain fiber optical strain sensors for railroad applications. The sensor system developed by UIUC consists of FBG, a distributed feedback (DFB) semiconductor laser source emitting a single-wavelength light, and optical isolators. The optical-fiber sensors are attached to rail tracks for detection of vertical and lateral loads with both static and dynamic waveforms. The performance of the fiber-optical strain sensors is compared with electrical strain gage sensors. Test results demonstrate much better signal-to-noise ratio using FBG sensors than the electrical strain gage sensors.

PRINCIPLES OF OPERATION OF FIBER BRAGG GRATING SENSOR

FBGs are periodic gratings imprinted on optical glass fibers by high intensity ultraviolet interference patterns. Gratings form reflections that result in changes in spectral behavior, and the reflected wavelengths are related to the period/spacing between gratings by:

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where n_{eff} is the effective index of refraction, Λ is the grating spacing, and λ_B is the reflected wavelength — known as the Bragg wavelength. Strain and thermal responses of FBG around 1500 nanometers (nm), due to mechanical properties and the effects of fiber thermo-optic, respectively, are a 0.05 nm shift in center wavelength per 50 $\mu\varepsilon$ and a 0.01°C per nm shift.[1,2] Combining the effects of thermal and strain on wavelength shift produces the simple linear relationship:

$$\left[\frac{\Delta\lambda_B}{\lambda}\right] = C_S\varepsilon + C_T\Delta T \qquad (2)$$

where C_T and C_S are constants. A practical system, however, will need to separate the temperature and strain effects. There have been extensive studies on how this can be achieved,[3] but this was not the focus of this study.

CONTROLLED LOAD EXPERIMENT WITH MULTIPLE SENSORS

This experiment was performed to measure and to be able to distinguish between vertical and lateral forces on a rail track. Three FBG sensors were installed on a 44-feet-long rail track section for a more realistic test condition. Controlled loads (sine, triangular and square waves) were applied both vertically and horizontally as Figure 1(top) shows. The system setup, as Figure 1(bottom) shows, consisted of two narrow-band DFB lasers (1547 nm and 1550 nm center wavelengths) with their output laser lights coupled into a single fiber through a two-by-one coupler. Both laser lights propagate through two FBG sensors with center wavelengths slightly above the wavelengths of the DFB lasers (matched to -3dB power loss point of the DFB lasers) with high reflectivity (~98%). The reflected spectrum was then passed through an optical filter (in this case another fiber Bragg grating) to separate the laser signals reflected from the two sensors. Finally the individual signals were detected by photodiodes and converted to electrical current signals. The system was designed such that when the rail experiences compressive strain, the voltage increases; it decreases with tensile strain. The system was demonstrated to have negligible crosstalk as two different time-varying forces are applied to two sensors located at two different positions, as Figure 2 shows.

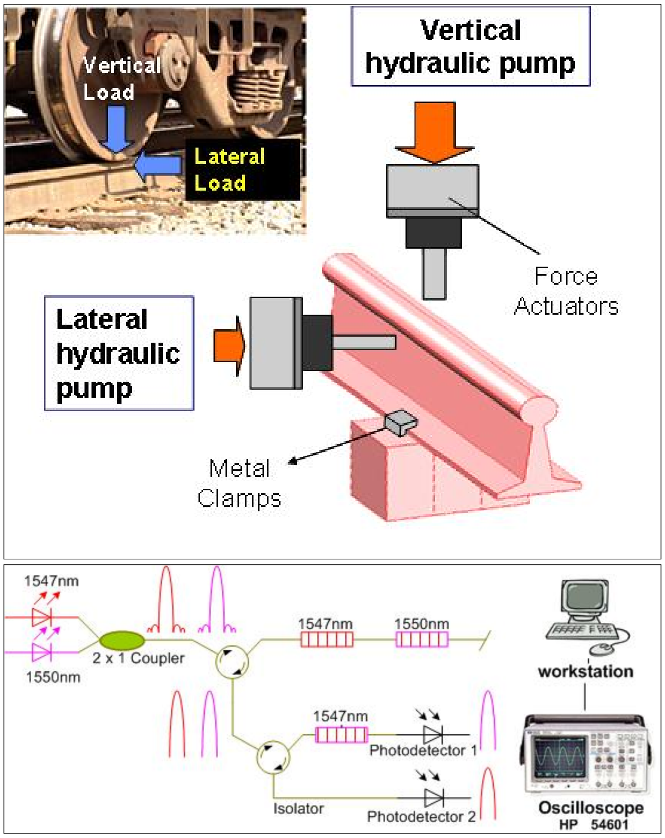

Figure 1. (top) Controlled-Load Actuators and Track Setup (bottom) System Setup to Integrate Multiple Sensors on a Single Fiber

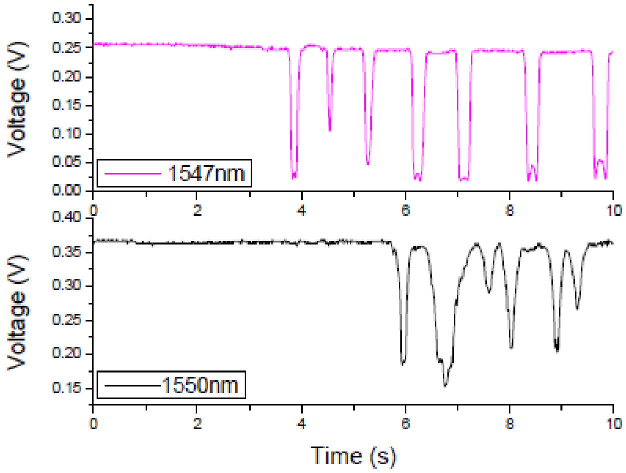

Figure 2. Output from Two Sensors on a Single Optical Path showing Negligible Crosstalk

Figure 3 shows a comparison between a FBG sensor (left) sensor and an electrical strain gage sensor for loads of 0.5, 1, 2, 3, 5 and 15 tons (from bottom to top waveforms), respectively. The two insets show the expanded scales for the bottom three loads at 0.5, 1 and 2 tons, respectively. Note the clean data curves for the FBG sensor on the left compared to the more significant noises on the strain gage sensor shown on the right inset.

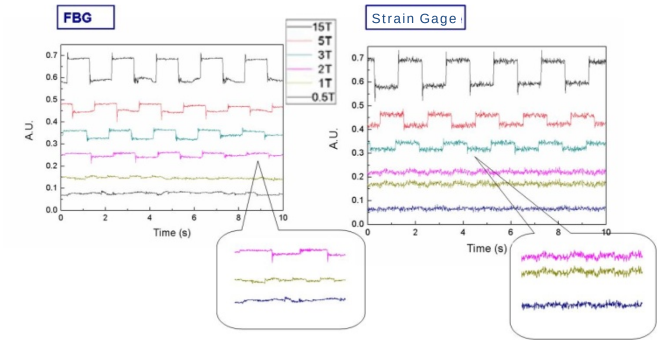

Figure 3. Vertical Load Sensitivity Comparison between FBG Sensor (Left) Sensor and Electrical Strain Gage Sensor (Right)

In order to decide how far apart to place the sensors, it is useful to find out the position dependence to correctly interpret the force exerted by each wheel on the track. First the position dependence of the magnitude decay of the FBG sensor response to where the force was applied using a single sensor was measured. A square wave force (25 tons in magnitude at 2-second intervals) was applied vertically directly above Sensor 1 and 7 inches away from Sensor 2. As displayed in Figure 4, at 7 inches away from the position of applied force, the output at Sensor 2 has decayed to one third of the original at Sensor 1.

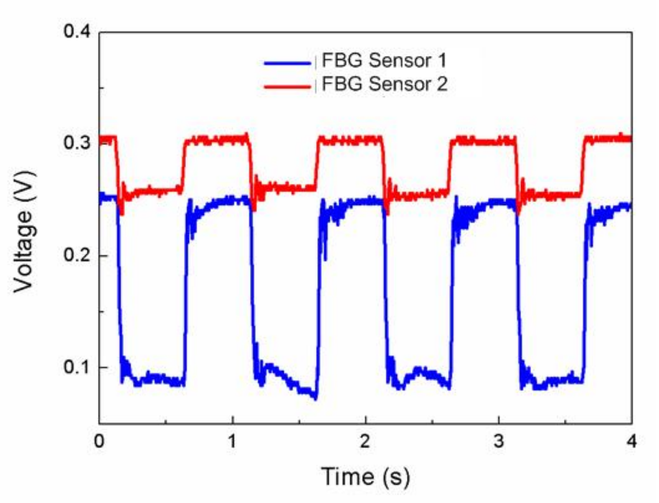

Figure 4. The Optical Power Responses of Two Sensors with Sensor 2 7 Inches away from Sensor 1 where the Force is Applied (Position 1)

As previously mentioned, fiber-optical sensors exhibit superior noise and sensitivity performance compared to electrical strain gage sensors. The sensitivity of the FBG system was analyzed and compared to conventional electrical strain gage sensors under controlled load conditions. Periodic square waves of varying magnitudes were applied vertically on top of the sensors at 2-second intervals. The magnitudes of the forces applied varied from 0.5 ton to 15 tons, and the results were recorded and are displayed in Figure 3. Figure 3 also shows a magnified view of the output waveforms for weight forces of 0.5, 1, and 2 tons for the bottom three curves. It is clear that for the FBG sensor, the 2-ton square waveform can be easily distinguished, while the strain gage reading shows no periodic structure, which concludes that the FBG sensor has better sensitivity than the electrical strain gage sensors under a vertical loading of 2 tons.

A similar test was performed for loading applied laterally to the rail. Both the electrical strain gage sensor and FBG sensor were placed vertically on the top portion of the rail, as Figure 5 shows. This is because bending is expected to occur in the –z direction (downward), and it is best to keep either above or below the neutral axis to avoid cancellation of strain due to compression and tensile forces. The result of applying a periodic square wave of magnitude 0.1 to 0.8 ton is also displayed at the bottom of Figure 5. Under this setup, 0.8 ton was the maximum lateral force that could be applied to avoid damaging the bottom hydraulic pump.

Compared to the clean square wave signals shown earlier in Figure 3, the waveforms look rounded for both FBG and strain gage sensors. Observations showed that during data recording, physical movement of the rail under lateral load sitting on a hydraulic pump is not as “clean-cut” as would be expected for the controlled loading square waves. Therefore, the rounded edges of the output waveforms of the sensors are expected and do represent the force pattern acting on the rail. Figure 3 shows that the FBG sensor has significantly better sensitivity for a small load of 0.1 ton compared to the strain gage sensor, which loses its resolution at around 0.5 ton of lateral loading.

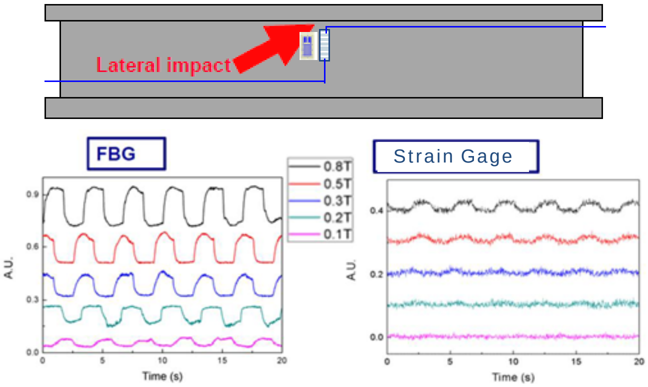

Figure 5. (Top) FBG Sensor and a Strain Gage Sensor to its Left (Bottom) Corresponding Waveform Responses of the FBG Sensor (Left) and Strain Gage (Right) Due to 0.1 to 0.8 Ton of Lateral Force

One of the motivations for using FBG sensors was to detect lateral and vertical forces simultaneously. To see this effectively, a square wave was applied in the vertical direction at 1 Hz, and saw-tooth waveforms were applied in the lateral direction with varying frequencies. Figure 6 records the FBG sensor output waveforms obtained for only a vertical load of 0.3 tons at 1-Hz square waveform (bottom curve), and those with the addition of a saw-tooth lateral load of 0.2 tons at 0.3 Hz (center) and 0.4 Hz (top). The FBG sensor system has the capability to detect and distinguish both lateral and vertical forces. This is useful because the FBG sensor system can separate the strain effects of lateral and vertical force components.

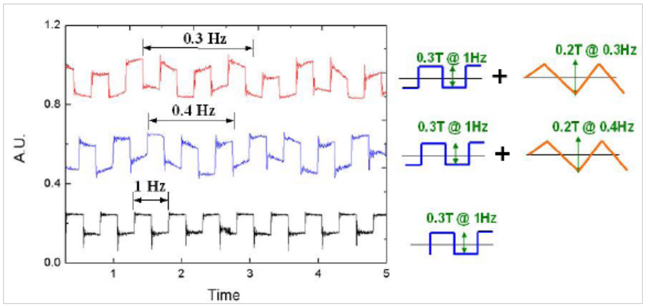

Figure 6. Measured Responses of the FBG Sensor Due to a 1-Hz Square Wave Vertical Load, Bottom: With No Lateral Load Applied, Center: With an Additional Lateral Impact at 0.4 Hz, Top: With an Additional Lateral Impact at 0.3 Hz

CONCLUSIONS

A system with multiple FBG sensors on a single fiber was implemented with negligible crosstalk. Results showed that the optical sensors have superior performance with better sensitivity and less noise compared to conventional strain gage sensors. The FBG sensors can detect as little as 1 ton of vertical loading and 0.1 ton of lateral loading. Results also showed that a single FBG sensor can detect and distinguish both lateral and vertical loads with time varying dependence.

FUTURE WORK

A field test is required to gain practical experience with the FBG sensor technology and to assess the durability of the sensors. Development of practical field repair procedures is also needed.

ACKNOWLEDGMENTS

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