Title: *Utilization of Fiber Optic Bragg Grating Sensing Systems for Health Monitoring in Railway Applications*

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ABSTRACT

We present results of a fiber optic structural health monitoring (SHM) system on an operational passenger railroad in Hong Kong. The system is based on a network of FBG sensors that measure strain and temperature in a multitude of critical locations. The sensors are mounted on guiding rails as well as on the under-carriage of passenger cars, using specially packaged strain sensors.

The system—which is fully operational and in present service use—is providing invaluable and timely information about stresses experienced during service, both static and dynamic, under different operational conditions. The sensors also provide information on the loading and traffic status of the passenger cars; temperature-induced stresses and deformations on rails and carriages; temperatures in and around axles and wheel brakes; dynamic axle vibrations due to corrosion and bearing wear; and other parameters relevant to railroad health monitoring.[1]

1. THE NEED FOR SENSING AND SHM IN THE RAIL INDUSTRY

The ever increasing need for improved safety, reliability and efficiency is among the most important aspects of the railway industry worldwide. On-board computers and train condition monitoring systems, as well as wireless data transmission are some of the tools than can fulfill such need. A smart condition monitoring system would allow real-time and continuous monitoring of the structural and operational conditions of trains as well as monitoring of the structural health of rail tracks and the location, speed and weight of passing trains of the entire rail systems. Ultimately, the inclusion of train location, speed restrictions, and train and track conditions to an 'intelligent system' will herald a safer railway industry

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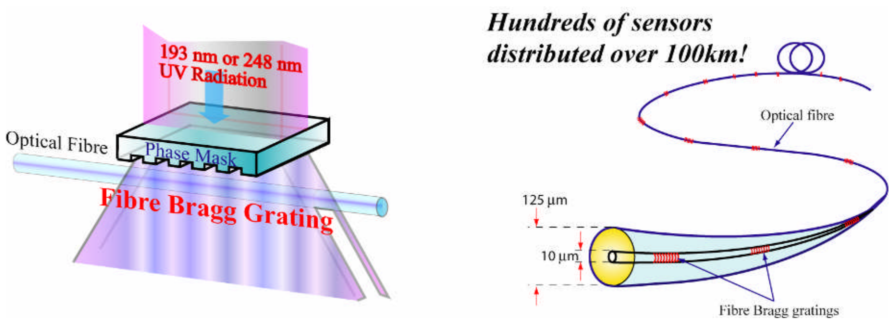
with reduced maintenance costs, optimized performance and capacity.

Therefore, the need of a smart condition monitoring system is imminent as indicated by the increase in railway and underground accidents/incidences around the world. Railway monitoring requires extensive sensor networks (1,000s of sensors) for measuring strain, vibration, temperature, acceleration, etc. This would be difficult and cost-prohibitive to implement using conventional sensors. Fiber optic sensors, on the other hand, offer many advantages over electrical sensors. These include immunity to EMI, long life-time (>20 years), and massive multiplexing capability - hundreds of sensing points along a single strand of optical fiber with length up to 100 km!

2. FIBER BRAGG GRATING SENSORS

Over the last few years, optical fiber sensors have seen increased acceptance and widespread use for structural sensing and health monitoring applications in composites, civil engineering, aerospace, marine, oil & gas, and smart structures. One of the newest application areas to adopt the use of fiber sensors—and in particular fiber Bragg gratings (FBGs)—is the railway industry, where it is of utmost importance to know the structural condition of rails, as well as that of cargo and passenger cars to ensure the highest degree of safety and reliable operation.



(a) (b)

Figure 1. (a) FBG fabrication using phase mask; (b) FBG sensor array for distributed sensing.

FBGs [1,2] are very small, short-length single-mode fiber devices (down to 0.5 mm) that display a periodic refractive-index variation in its core, as shown in Fig. 1. The reflection wavelength is sensitive to temperature and strain with corresponding wavelength-shift of 10pm/°K and 1pm/microstrain. FBG measurements are wavelength-encoded and immune to intensity fluctuations. Therefore self-referencing (no recalibration/re-initialization) is possible with FBG sensors which is an important feature for safety critical industry such as railways. Furthermore, fiber Bragg grating sensors can be interrogated at very high-speed of up to 500 kHz.

Multiplexing large number of FBGs over long distance is particularly important for condition monitoring applications in railways. Fig. 2 shows the schematic of a possible FBG sensing configuration for measuring many different parameters on train wagons using one FBG interrogator. Commercial FBG interrogators with the capability of dealing with 100's FBGs with 0.05 pm resolution at 1,000 sampling/second are available [3]. Some of the potential applications of FBG sensors in the railway industry are shown in Fig. 3.

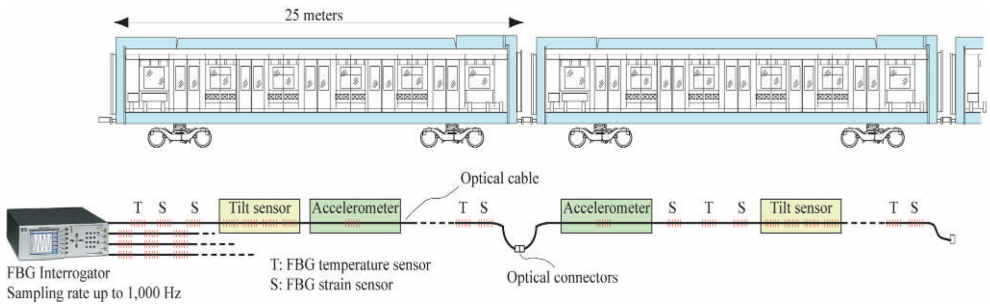


Figure 2. Multi-functionality of FBG sensors - FBG arrays for the measurement of temperature, strain, tilt angle, and acceleration of train wagons using a commercial FBG interrogator.

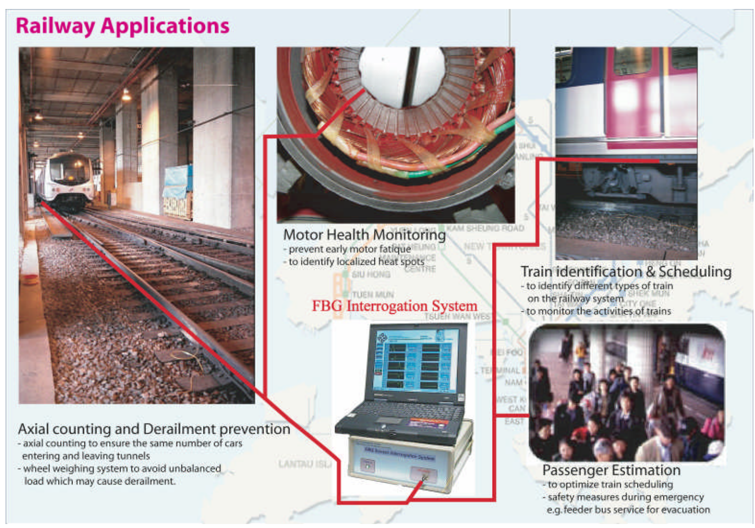


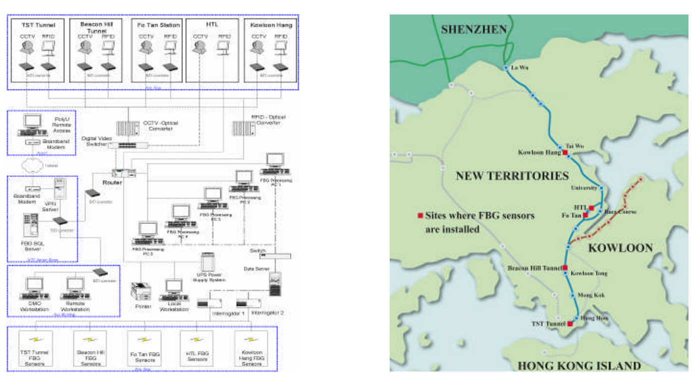
Figure 3. Many railway parameters currently being monitored using different conventional electrical sensor systems as shown in the figure could be replaced by FBG sensor networks.

3. APPLICATIONS OF FBG SENSOR ARRAYS IN RAILWAYS

Over the past couple of years, the Department of Electrical Engineering at the Hong Kong Polytechnic University has been conducting several collaborative R&D projects with the Kowloon-Canton Railway Corporation (KCRC) employing FBG sensor arrays for temperature and strain measurements on train wagons, bogies and rail tracks using FBG interrogators and sensing instrumentation developed by Micron Optics Inc. of Atlanta, GA, USA. The ultimate goal of these projects is to develop the world's first *"Smart Railway Sensor Network"* by incorporating optical sensory nerves at various parts of the railway networks. These *"optical nerves"* can be extended to monitor other railway installations such as transformers and overhead power lines. Initially, the project involves the development and implementation of an optical fiber distributed sensor system that incorporates hundreds of Fiber Bragg Gratings (FBGs) in: 1) four trains (each consists of 12 wagons) to measure strain and temperature, and 2) five KCRC stations, for the measurement of strain in rail tracks to (a) serve as axle counters, and (b) monitor the instantaneous vibration signatures of passing trains at selected locations. These studies with KCRC have demonstrated that the application of FBG sensors along the rail tracks have the potential to revolutionize the railway industry and to update conventional systems into *'Smart Railways'*, thereby providing safe, reliable and vital information to rail operators. The FBG sensors can be used to monitor many important railway sub-systems such as axle counters, anti-derailment monitors, train load detectors as well as serving as continuous rail crack detectors. This permits real-time monitoring of the entire rail network, allowing maximization of network capacity, optimization of electricity utilization and effective detection of potential operational hazards to enhance overall service safety and quality.

3.1 Speed and Weight Measurement using FBGs

Fig. 4 (a) shows the schematic diagram of a train monitoring system installed on five sites along the KCRC's East Rail [4-7]. East Rail is about 36 km long and run from Tsim Sha Tsui (TST) station to Lo Wo station (Fig. 4 (b)). The sites are equipped with Radio-frequency identification (RFID) systems to record the identity (ID) of each wagon that passes through them. Each site was also installed with about ten FBG sensors on the rail tracks to measure the strain induced on the tracks when a train passes over them. Consequently, the strains or vibration measured by the FBG sensors can be traced back to the wagons by their IDs. The FBG sensors are epoxied on the rail tracks and are connected by armored optical cables to an optical fiber backbone that runs along the entire route of the East Rail. All FBG sensors are eventually connected to a FBG interrogator (Micron Optics Inc.) located in the depot at Ho Tung Lau (HTL).



(a) (b)

Figure 4. (a) Schematic of FBG rail track monitoring system installed on 5 KCRC railway stations, (b) Locations of the five sites where FBG sensors are installed.

Fig. 5 shows a typical measured result of an FBG installed on a KCRC rail track. Each individual wheel passing through the FBG sensor is clearly identifiable. The minimum induced strain due to a wheel passes on the track is more than 120$\mu\varepsilon$

and the noise is less than 5με, giving a SNR of better than 17dB. For comparison, a typical received signal from a conventional magnetic axle counter is also shown in the inset of Fig. 5. Since the distances between the wheels are known, train speed can be easily computed by using just one FBG sensors. FBG sensors on rail tracks could thus be used as axle counters and at the same time provide important information for speed and weight measurements. We have employed FBG sensors as axle counters since 2002 and have never observed any miscount so far.

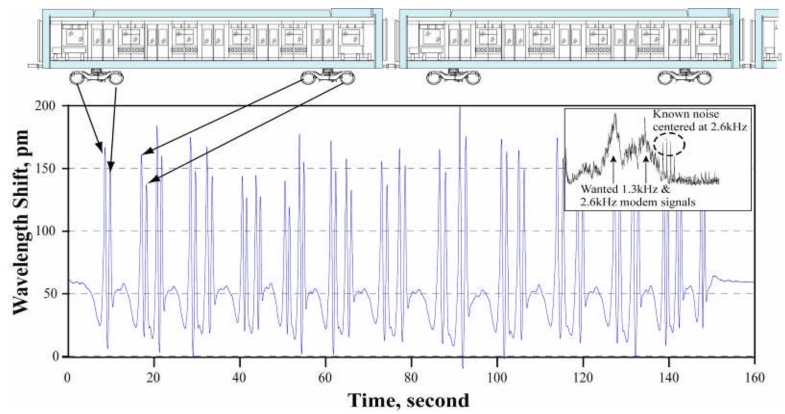


Figure 5. Measurement results of FBG sensors for counting train axles. Inset shows the received signal from a conventional magnetic axle counter for comparison.

FBG sensors can be installed on each side of a rail to detect imbalances on the two sides of rail wheels. It is well known that if there are large difference between the left and right hand side loading of an axle, there is the danger of train derailment. Thus, it is generally required for freight trains to go through a Wheel Weighing System (WWS). Conventional WWSs use strain gauge sensors to detect the train loading, train speed and to assess the possibility of derailment. The working principle of the strain gauge sensors is that when a train is residing on top of the rail—at which the strain gauge is installed—the resistance of this particular strain gauge is affected. The degree of imbalances in the bridge circuit can be calibrated to give an indication of the train loading. However, the system is expensive, bulky and can be adversely affected by electromagnetic interferences. Hence, conventional anti-derailment systems have to be installed at a selected location having extremely stringent shielding requirement to ensure the system is not affected by electromagnetic interferences. On the other hand, FBG sensors can be readily installed on the left and right rails (for the two wheels of the same axle) at low cost to measure the important parameters for the railway engineer in the monitoring of anti-derailment ratio of passing trains.

3.2 FBG Sensors for Assessing Structural Integrity of Train Body shells

We have also used FBGs for the measurement of strain and temperature of train body shells. The interrogation system uses a a swept, broadband, tunable fiber laser source to detect the peak wavelength of each FBG within the array. A NIST traceable wavelength reference is used to ensure high accuracy and repeatability with every measurement scan. The strain measurement resolution of the system is of the order of 1με with a sampling frequency of better than 10Hz. The system allows about 10 FBG sensors of different wavelengths to be connected serially, and be interrogated at the same time.

Six FBG sensors were installed on a trailer car and the same number of sensors was installed on the motor car of a train. For the trailer car, three of them were positioned at the corners of the window frame as shown in Fig. 6 with one at the bottom steel bar, while the other two were at the top surface of the car. For the motor car, four out of six FBGs were installed at the four corners of a window frame. The other two were located at the top surface and the bottom steel bar, respectively. A similar number of electrical strain gauges were located in close proximity to the FBG sensors and the results from FBG sensors agree well with the electrical strain gauge.

Fig. 7 shows the dynamic strains measured from FBG and the strain gauges installed on the window frame of the motor car, when the train was running from Lo Wu (time: 0 second) to Hung Hom (time: 2500 second) station. The results from the two type of sensors, for most of the parts, agree with each other with maximum changes of strain occurring at about 2000 seconds (at Kowloon Tong Station where many people got off from the car) and the strains were reduced to small values when people alighted the train at Lo Wu and Hung Hong terminus. However, there are two noticeable differences between the results from the FBG and the electrical strain gauges. The first is that the high frequency dynamic strain due to the movement and vibration of car is more clearly picked up by the FBG sensor than by the strain gauge. This is because that the FBG system responses faster than the strain gauge (the response time of the FBG system was about 0.1 second while the strain system was about 1 seconds). The other difference is the large output signals from the strain gauges at around 1100 second (in between Tai Po Market and University Stations) when the train passed through a neutral section at which the high tension power was switched OFF and ON as the train went through the neutral section. This is, however, not reflected at all at the FBG sensor output, indicating superior performance of the FBG sensors because of their immunity to EMI.

3.3 Dynamic Strain Monitoring at Weld Joints

FBG sensors have also been installed on a number of equipment in the under-frame of trains for monitoring the vibrations in critical locations which include the welding joints, cross beams and sole bars as shown in Fig. 8. In particular, the vibrations measured at the welds are converted into an equivalent fatigue index using the S-N curve quoted in the BS7608:1993 standard as shown in Fig. 9. Such index is highly instrumental in the prediction of the life expectancy of the trains. Fig. 10 shows typical strains picked up by the FBG sensors at different locations. A wealth of information could be extracted from these measurements. For instance, the frequency spectrum of the vibrations could be analyzed and checked for any conspicuous signatures close to the resonance frequency of the train body.

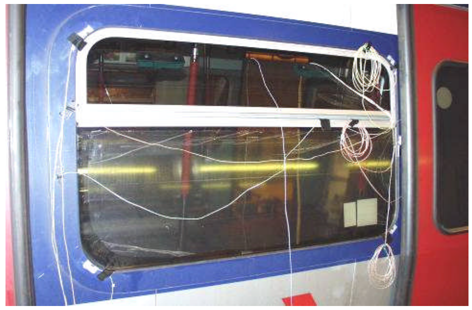
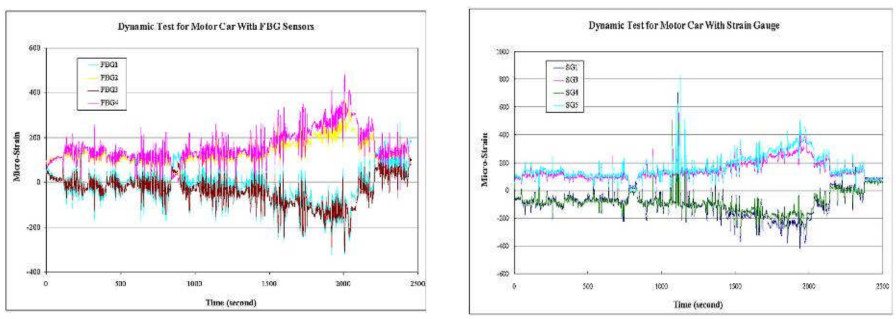


Figure 6. Strain gauges instrumented on a train car for assessing its structural integrity.



(a) (b)

Figure 7. Results of dynamic load test. (a) FBG sensors; (b) electrical strain gauges. Note that the FBG sensors are immune from the strong EMI picked up by the strain gauges around 1100 seconds.

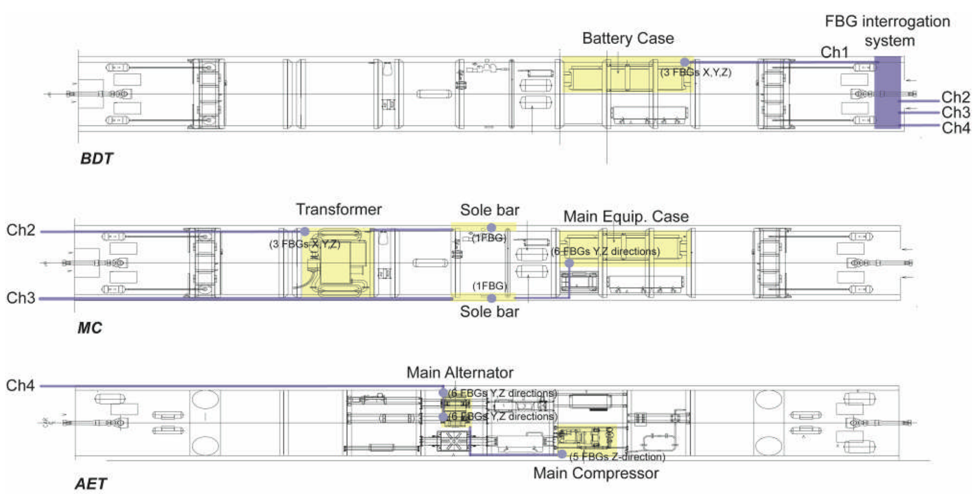


Figure 8. Locations of weld joints where FBG sensors are installed for monitoring dynamic strains of critical parts: BDT = Battery Trailer, MC = Motor Car, AET = Auxiliary Equipment Trailer.

The level of self-generated vibrations—due to local compressor or motor-alternator—could also be checked. Measured strains on train-borne equipment allow the operators to determine whether any rail sections have excessive vibrations and whether it is necessary to carry out any rail tamping or polishing. In short, sensors installed on board of trains can be used to monitor the vibrations of train borne equipment as well as perform surveillance of track conditions. While track-based sensors, are used to monitor vibrations induced by all passing trains.

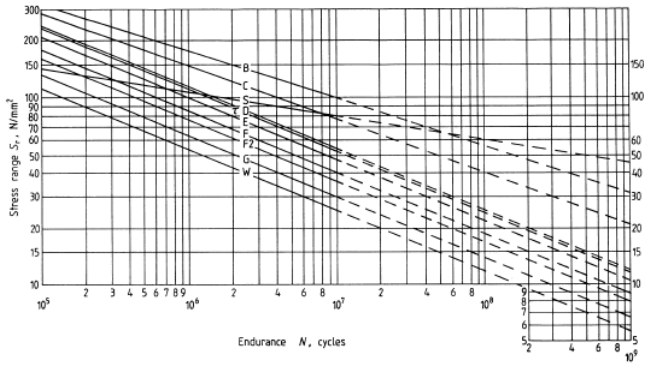


Figure 9. Summary of standard basic design of Sr-N curves (extracted from BS 7608:1993).

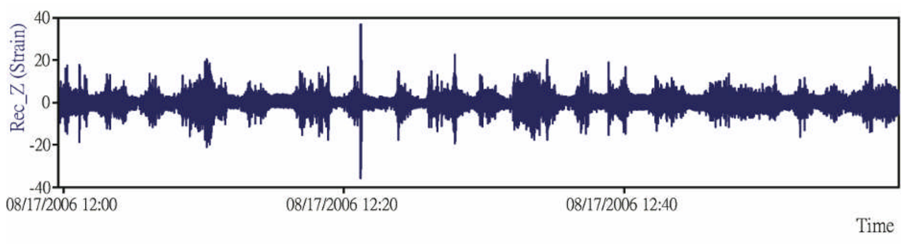


Figure 10. Dynamic strain measurements with FBG strain sensors epoxy-bonded on weld joints.

CONCLUSIONS

Two distinct SHM systems—based on FBG sensors—were designed and integrated by The Hong Kong Polytechnic University in collaboration with KCRC. One system was installed on the rail tracks and was used for the detection of wheel/rail interface response; and second one installed on board of train cars. The field measurement results coupled with the experiences gained from this project demonstrated that the utilization of FBG-based systems can be a practical and effective tool for on-line condition monitoring systems for the railway industry.

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