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Fiber Bragg Grating Sensors for Structural and Railway Applications (Invited Paper)

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Abstract

Historically, due to the high cost of optical devices, fiber-optics sensor systems were only employed in niche areas where conventional electrical sensors are not suitable. This scenario changed dramatically in the last few years following the explosion of the Internet which caused the rapid expansion of the optical fiber telecommunication industry and substantially driven down the cost of optical components. In recent years, fiber-optic sensors and particularly fiber Bragg grating (FBG) sensors have attracted a lot of interests and are being used in numerous applications. We have conducted several field trials of FBG sensors for railway applications and structural monitoring. About 30 FBG sensors were installed on the rail tracks of Kowloon-Canton Railway Corp. for train identification and speed measurements and the results obtained show that FBG sensors exhibit very good performance and could play a major role in the realization of "Smart Railway". FBG sensors were also installed on Hong Kong's landmark TsingMa Bridge, which is the world longest suspension bridge (2.2 km) that carries both trains and regular road traffic. The trials were carried out with a high-speed (up to 20 kHz) interrogation system based on CCD and also with a interrogation unit that based on scanning optical filter (up to 70 Hz). Forty FBGs sensors were divided into 3 arrays and installed on different parts of the bridge (suspension cable, rocker bearing and truss girders). The objectives of the field trial on the TsingMa Bridge are to monitor the strain of different parts of the bridge under railway load and highway load, and to compare the FBG sensors' performance with conventional resistive strain gauges already installed on the bridge. The measured results show that excellent agreement was obtained between the 2 types of sensors.

1. Introduction

Photosensitivity in fiber and the resultant index gratings were first demonstrated in 1978, by Ken Hill *et al* [1] during experiments using Ge-doped silica fiber and visible argon ion laser radiation. The grating was formed by the standing wave in the fiber and thus its reflection wavelength is close to that of the writing light. In 1989, however, Gerry Meltz et al [2] demonstrated a holographic technique of "side" writing Bragg gratings using UV light at 244 nm. This allows reflection gratings at virtually any wavelengths to be fabricated. A number of key technologies developed in recent years encourage the widespread use of fiber Bragg gratings (FBG).

One of the most successful applications of FBGs is perhaps as wavelength lockers for wavelength stabilization of 980 nm and 1480 nm pump lasers. Other popular applications of FBGs in optical communications include fiber grating lasers, gain flattening filters for erbium-doped fiber amplifiers and dispersion compensation.

Fiber gratings based sensor systems are now being used in large number of applications ranging from structural monitoring of bridges, dams, railroad tracks, airplane wings to chemical sensing.

These tiny optical fiber sensors known as "fiber Bragg grating sensors" are fabricated inside the 10 micron-core of standard telecommunication optical fibers. An FBG interrogation system can handle more than 100 FBG sensors created inside a single fiber. This unique feature open the opportunities for them to be used in many applications that otherwise would not have been possible. Another important advantage of this type of optical fiber sensors is their inherent immunity to electromagnetic interference that made them ideal for the electrical engineering industry where EMI and hazardous environment are major concerns for electronic sensors.

2. Fiber Bragg Grating Sensor Technology

Figure 1 shows the phase mask writing technique which is widely used to fabricate FBG because it is a much simpler process than the holographic technique and can produce high performance gratings. The reflection or Bragg wavelength of the FBG formed depends on the pitch of the phase mask and the fiber itself.

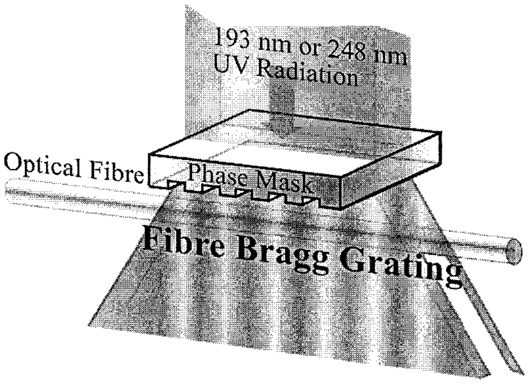


Figure 1: Fabrication of FBG inside the 9-µm core of a standard telecommunication fiber using a phase mask.

FBGs couple the forward propagating core modes to the backward modes at the wavelength, λ_B, that satisfy the resonance condition

$$\lambda_B = 2n\Lambda, \tag{1}$$

where n is the effective index of the core mode and Λ is the period. FBGs with up to ~100% reflection are routinely being fabricated. Figure 2 shows typical reflection spectrum of an FBG.

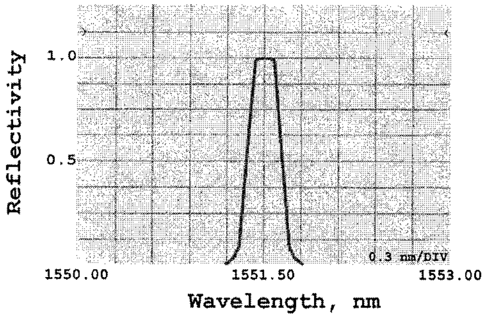


Figure 2: Typical reflection spectrum of a high reflectance FBG sensor.

The basic principle of operation in fiber grating-based sensor systems is to measure the Bragg wavelength shift of FBGs. FBG has a very narrow reflection spectrum (~0.2 nm) and therefore many such sensors (up to 100) with different reflection wavelengths could be multiplexed on a single fiber. FBG sensors are very attractive and are being used in many applications that require many tens and even hundreds of sensors. Typical strain and temperature responses of FBG are 1 pm/$\mu\varepsilon$ and 11pm/°C, respectively, at the Bragg wavelength of 1550 nm. Since FBG sensors are sensitive to strain as well as temperature, two FBG sensors are generally required for measuring strain, with one FBG attached to the structure for strain measurement and the other FBG in close proximity for temperature compensation.

Obviously, the performance of an FBG sensor system depends very much it's capability to measure accurately the Bragg wavelength shift of FBGs with adequate resolution. In some applications, such as in the velocity measurement of train, high speed detection may be needed. Several techniques are available in measuring the wavelength shift of FBG sensors. Since FBGs are passive devices, broadband optical light sources are required to illuminate FBG sensors. The reflected wavelength could be measured by using optical spectrum analyzers, tunable bandpass optical filters, or linear optical filters.

One of the main advantages of FBG sensor technology is that may such sensors could be created inside a single optical fiber and be interrogated by accessing just one end of the fiber. Two general approaches, namely, wavelength-division multiplexing (WDM) and time-division multiplexing (TDM), are being employed to interrogate multiple FBG sensor arrays. WDM interrogation systems typically require highly reflective FBG sensors each operating in distinct wavelength windows. Figure 3 shows the schematic of a scanning filter FBG interrogation system based on WDM technique. Commercial FBG interrogation systems based on scanning F-P filters are available from several companies. The maximum number of FBG sensors along a single fiber that could be interrogated by a WDM interrogation unit depends on the optical bandwidth of the light source, operation range of each FBG sensors and the tuning range of the tunable filter. The typical number of FBG sensor that can be dealt with by an WDM interrogation unit is about 40 and is mainly limited by the light source's optical bandwidth.

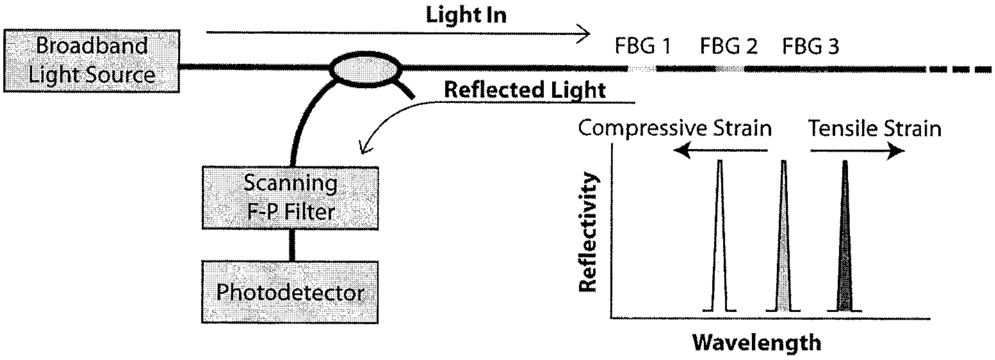


Figure 3: FBG interrogation using a scanning Fabry-Perot optical bandpass filter.

TDM systems utilize identical, low reflectivity FBGs (typically 4 % reflection) all operating in the same wavelength window. Fig. 4 shows the schematic of a TDM interrogation system where narrow optical pulses were launched into an optical fiber containing many FBGs with virtually identical Bragg wavelength. Light takes about 10 ns to propagate one round trip along 1 m of optical fiber and therefore the separation between adjacent sensors must be greater than 1 m for interrogating pulses of 10 ns wide. Individual sensors are distinguished by measuring the time of flight of signals returning to the interrogation unit. A single optical pulse consists of many wavelength components but FBG sensors reflect only the wavelength component that matches to their Bragg wavelength. Normally, the wavelength shift of the sensor is determines by using a linear optical filter which converts wavelength shift to optical power variation. However, the signal-to-noise ratio of TDM systems is lower than that of WDM systems and therefore the performance of TDM systems is generally not as good as that of WDM systems. The wavelength measurement accuracies demonstrated by WDM interrogation systems and TDM interrogation systems are typically 1 pm and 10 pm, respectively. This is equivalent to temperature and strain measurement accuracies of 0.1°C (1°C) and 1 $\mu\varepsilon$ (10 $\mu\varepsilon$), respectively, for WDM (TDM) interrogation units. For comparison, the complexity of a conventional electrical sensor with its associated conditioning electronics is shown in fig. 5. Multiplexing hundred of such sensors together can be quite a daunting task.

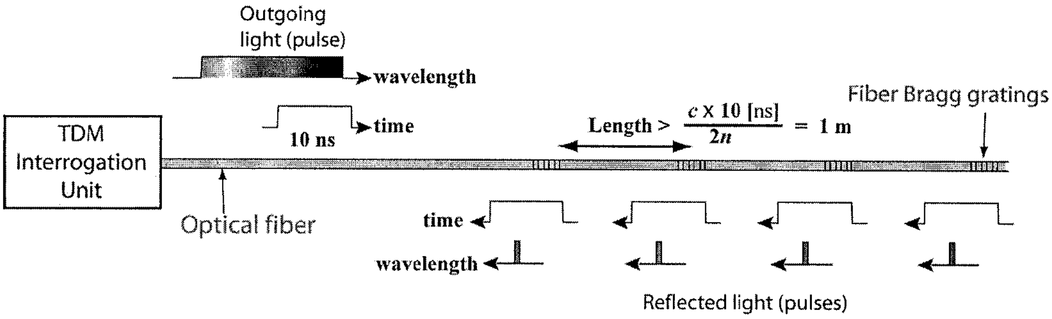


Fig. 4: TDM interrogation of multiple FBG sensors.

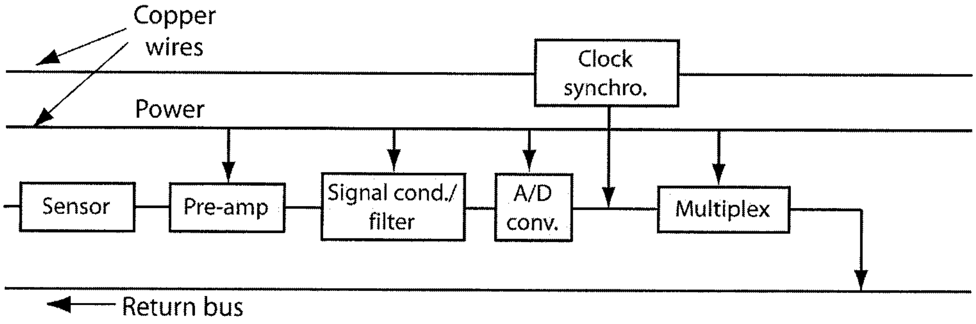


Fig. 5: Conventional electrical sensor with its associated electronics.

3. Applications of Fiber Bragg Grating Sensors

In the following sections, the field trials of FBG sensors on railway tracks to measure the speed of trains and on a bridge for strain and temperature monitoring will be described. These fiber-optics sensors were installed on several railway stations of the Kowloon-Canton Railway Corp., (KCRC) in Hong Kong for the detection of the passing of trains. Forty FBG sensors were also installed on Hong Kong's landmark TsingMa Bridge for strain and temperature monitoring, and for comparing their performance with electrical strain gauges already installed on the Bridge.

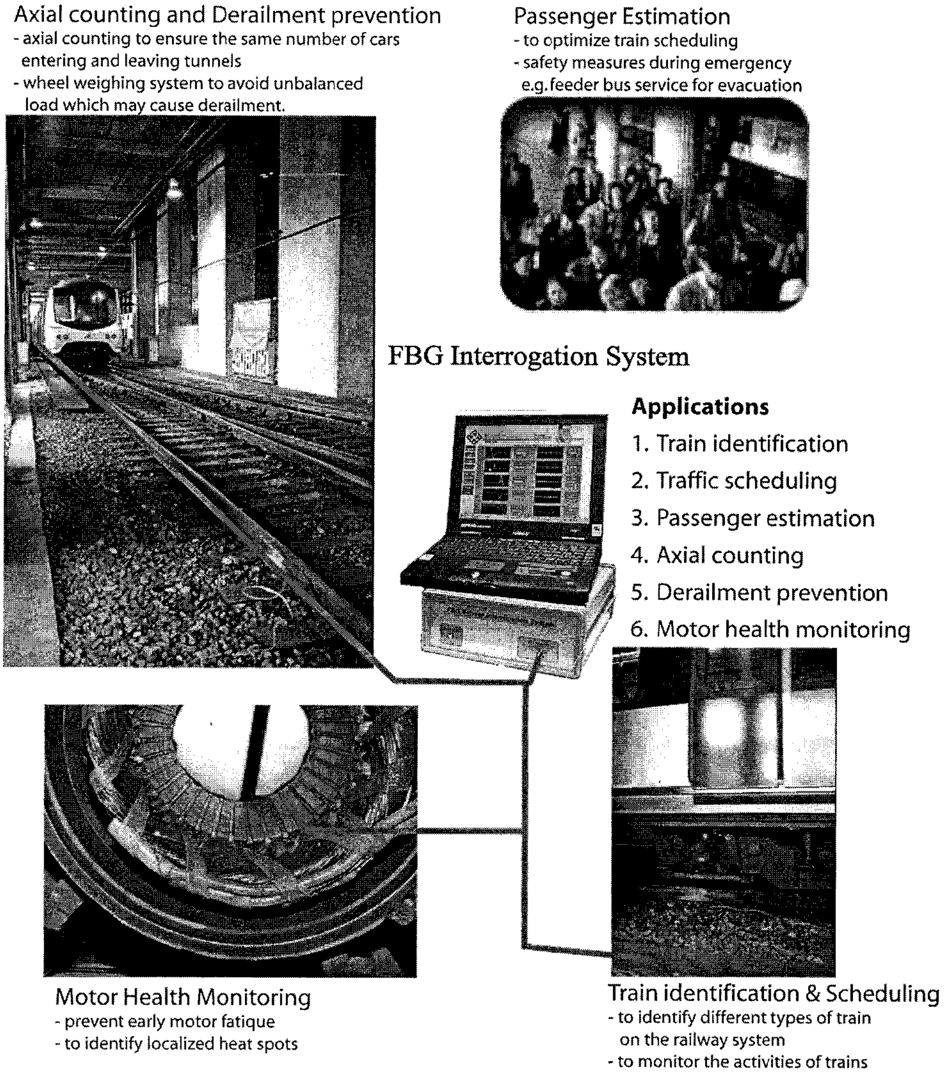
3.1 FBG Sensors for Railway Applications

The applications of FBG sensors in railway networks are enormous. Examples include axle counting, on-line measurement of train speed, train weight estimation, wheel imbalance weighting, train identification, detection of untoward activities, etc. FBG sensor system is best suited for railway monitoring due to its many unique features that are not found in electrical monitoring systems.

Some of the features of FBG sensors that are important to the railway industry are listed below.

a) ***EMI immunity*** – a serious concern as trains are power by high voltage overhead lines which generate high EM field. A case in point was the recent signalling problem of the West Rail in Hong Kong SAR caused by EMI and delayed its operation by several months.
b) ***Capability to multiplex large number of sensors along a single fiber*** – either of the two fiber ends could be used to interrogate all the sensors, greatly simplify installation and thus reduce cost. In addition, it provides an extra access point to enhance system reliability.
c) ***Remote sensing*** – FBGs are created inside standard optical fibers which exhibit extremely low loss, permitting interrogation of FBG sensors over long distances.
d) ***Inherent self-referencing capability*** –strain information is encoded in the FBG reflection wavelength which is an absolute parameter and thus the measurement value does not depend directly on the losses between FBGs and interrogation unit, offering better survivability of the sensor system.
e) ***Eliminate the needs for recalibration or re-initialization*** – makes possible by the wavelength-encoding nature of FBGs.

Incorporating FBG sensors in rail tracks has the potential to revolutionize railway systems into "Smart Railway". FBG sensors arrays offer real time monitoring of an entire rail network providing important information such as train location, train speed, estimation of train weight, condition monitoring of rail tracks, etc. Preliminary experimental investigation of FBG sensors in KCRC stations demonstrate the huge potential of FBG sensing system in locating train position, measuring train speed, estimating train weight, measuring wheel imbalance and so on. Fig. 6 shows some of the on going projects being conducted at some KCRC's rail tracks by researchers of the Photonics Research Centre of The Department of Electrical Engineering at The Hong Kong Polytechnic University.



Axial counting and Derailment prevention
- axial counting to ensure the same number of cars entering and leaving tunnels
- wheel weighing system to avoid unbalanced load which may cause derailment.

Passenger Estimation
- to optimize train scheduling
- safety measures during emergency e.g.feeder bus service for evacuation

FBG Interrogation System

Applications
1. Train identification
2. Traffic scheduling
3. Passenger estimation
4. Axial counting
5. Derailment prevention
6. Motor health monitoring

Motor Health Monitoring
- prevent early motor fatique
- to identify localized heat spots

Train identification & Scheduling
- to identify different types of train on the railway system
- to monitor the activities of trains

Figure 6: Applications of FBG sensors in railway engineering.

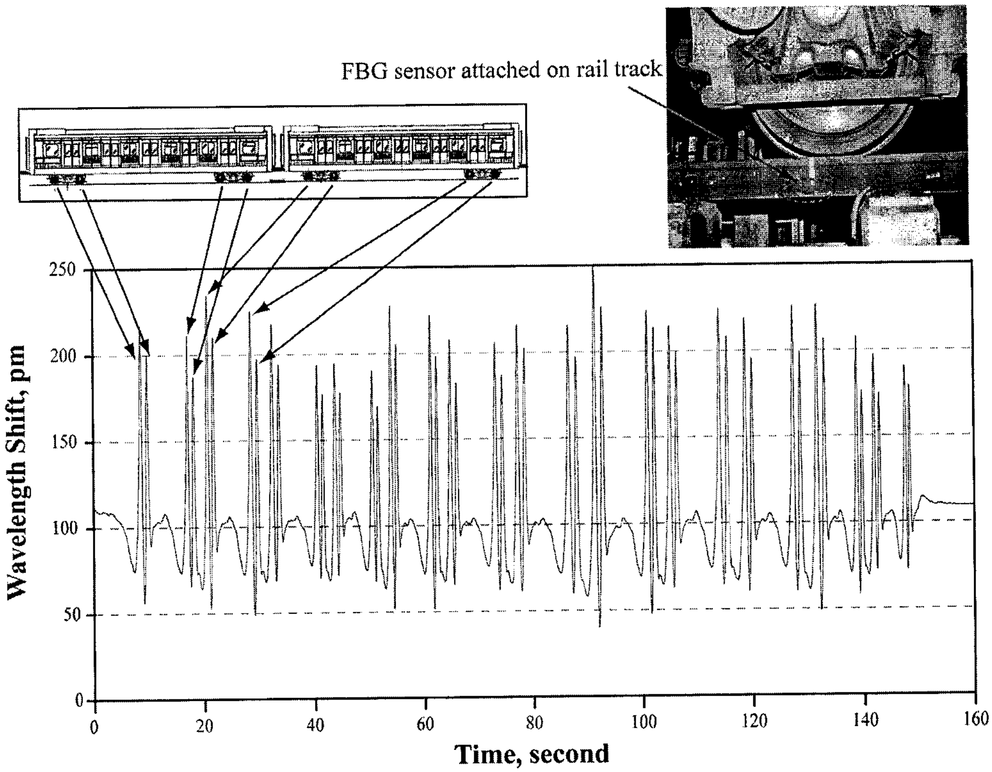


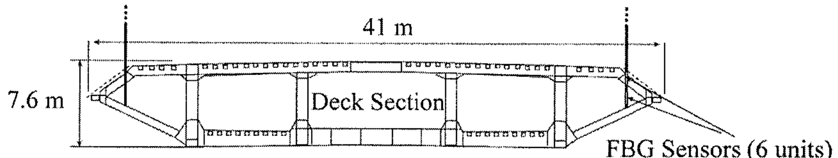
Figure 7: Experimental results of FBG sensor for train speed measurement. Inset shows the rail track with FBG sensor.

Figure 7 shows the measured result of an FBG installed on a KCRC rail track at the front end of one of KCRC station. Each individual wheel passing on top of the FBG sensor is clearly identifiable. Since the distances between the wheels are known, train speed can be easily computed by using just one FBG sensor. Alternatively, two FBG sensors installed on the rail track, separated by a known distance can also be used to measure train speed. In this particular example, the separation between two wheels of each axle is 2.5 m and the time taken for them to pass on top of the FBG sensor was about 1.1 seconds, so the train was traveling at about 8.2 km/hr. The last two wheels on the last car of the train took about 0.74 second to pass the FBG sensor and thus the last car was leaving the platform at a velocity of about 12.2 km/hr. It is interesting to note that the train acceleration, as it was leaving the station platform can also be measured.

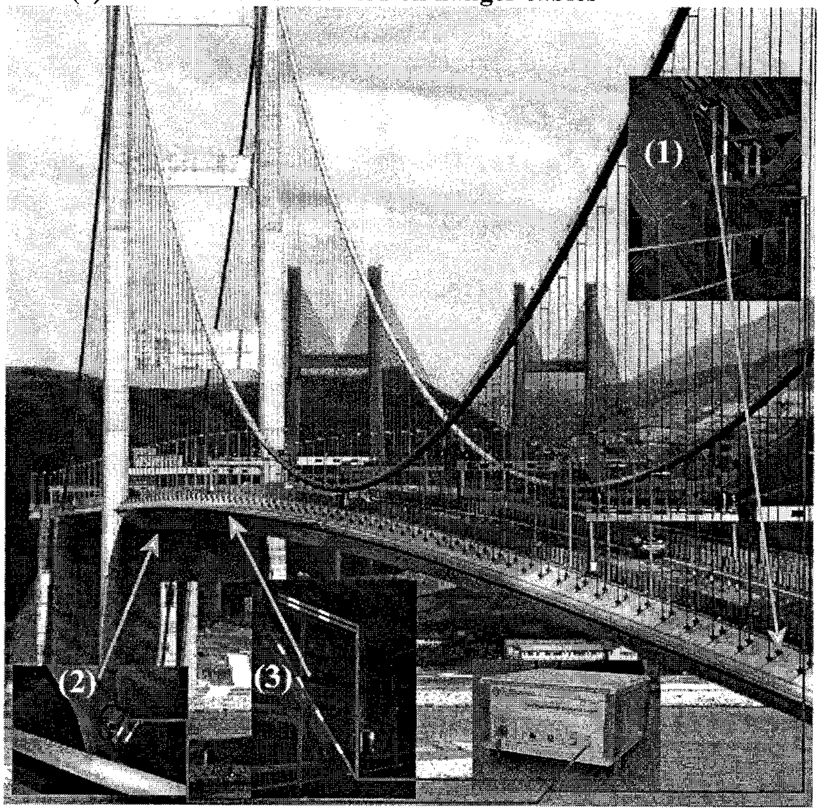
The magnitude of the wavelength shift, i.e. the amplitude of the peaks shown in the figure is related to the force applied to the sensor by the wheel passing over it. This information could be used to estimate the weight of a passing train if the track is properly calibrated.

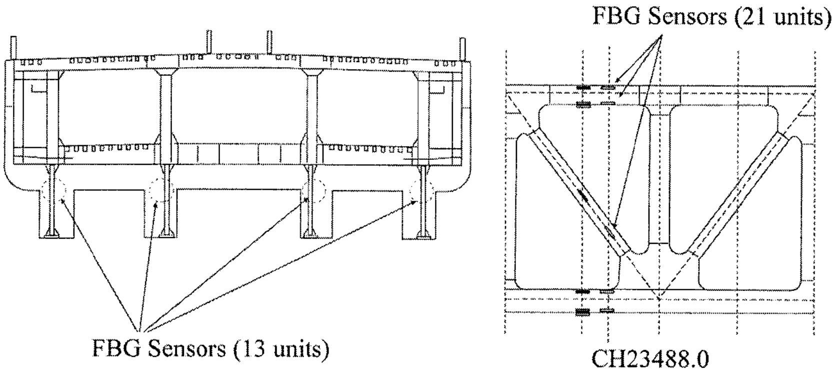
3.2 Monitoring of Tsing Ma Bridge using FBG Sensors

Sensors for strain measurement are indispensable for structural monitoring. Recently, we carried out a field trial with a FBG sensor array system on Hong Kong's landmark TsingMa Bridge which is the world's longest span suspension bridge that carries both trains and regular road traffic. The experiment was carried out with an FBG interrogator based on a scanning optical bandpass filter that provides a sampling speed of up to 70 sample/sec as well as with a high-speed interrogation system (DC to ~20 kHz for all channels simultaneously) based on CCD. 40 FBG sensors divided into 3 arrays were installed on different parts of the bridge (suspension cable, rocker and truss girders), as shown in fig. 8. The goal of this field trial is to monitor the strain of the different parts of the bridge under railway load and highway load. Various measurements were performed including an overnight measurement of about 20 hours with a sampling frequency of about 500 Hz. The measurement results reveal the presence of significant higher frequency components in the FBG sensor signal during train passages. The results of the FBG sensor were also compared with existing strain gauges. Although the sensors are not located at exactly the same location, great resemblance has been found.



(1) 6 FBG sensors installed on hanger cables





(2) 13 FBG sensors installed on 4 rocker bearings **(3) 21 FBG sensors installed on Chainage 23**

Figure 8: Forty FBG sensors are installed on the TsingMa Bridge to measure temperature and strain at (1) hanger cable, (2) rocker bearing, and (3) truss girders.

3.2.1 Sensor Packaging and Installation

Standard telecommunication single mode fibers (SMF 28) were used to fabricate the FBGs. In order not to weaken the mechanical strength of the FBG, the outer coating of the fiber was removed by soaking a short length of the fiber in warm acid bath instead of using mechanical stripper. After the FBG inscription, the un-coated FBG was annealed. To facilitate the installation process while maintaining the straightness of the FBG, the FBG was mounted on nitinol strips with thickness of 0.0029" and dimensions of 6×110 mm, which were cleaned with high concentration isopropanol to remove grease stains. The FBG-nitinol sheet combo were sandwiched and pressed together using two Teflon sheets to minimize the thickness of epoxy between the FBG and the nitinol sheets.

In order to protect the packaged FBG strain gauges form moisture and dust, weather proof ABS enclosures measure 120×80×60 mm that complied with IP65 were used. These enclosures are same as the electrical strain gauge enclosures in terms of functionality and appearance that are in-used by the Highways Department of Hong Kong SAR. To attach the packaged FBG sensor to the ABS enclosure, a rectangular opening was cut from the bottom of the enclosure so that the sensor can be attached to the structure through this opening. The sensor was then connected to more rigid 3 mm single mode optical fiber cables and led out from the enclosure through two stress relieving boots. In case where an extra FBG is needed for temperature referencing inside the enclosure, an FBG was connected to the strain sensing FBG before the 3 mm cable is connected. This temperature referencing FBG must be free from stress to avoid cross-sensitivity of strain and temperature [3]. To attach the FBG sensor firmly on the structure, a small area of this protective paint was removed. Attention was paid during the removal of paint to avoid damaging the steel beneath. Before attached the packaged FBG sensor, that area was cleaned with clear water and high concentrate isopropanol. Two types of adhesive glues were used to attach the enclosure and FBG sensor on the steel. Instant cyanoacrylate glue was applied on the outer rim of the enclosure base and, on the inner rim of the enclosure and FBG sensor, a two-part weather proof epoxy was used. The combination of using two glues at different position held the sensor package securely in place while the strong bonding epoxy was being cured.

Three strands of fibers, in which up to 21 FBG sensors were serially connected, were installed in the rocker bearing, supporting structure on a section of lower deck of Chainage 23 and suspension cables. Figure 9 depicts the three FBG sensors in one of the rocker bearings. One of the FBG sensors was installed close to a resistive strain gauge in-used in the bridge. A computer was used with the interrogation system to transfer commands and to record experimental data.

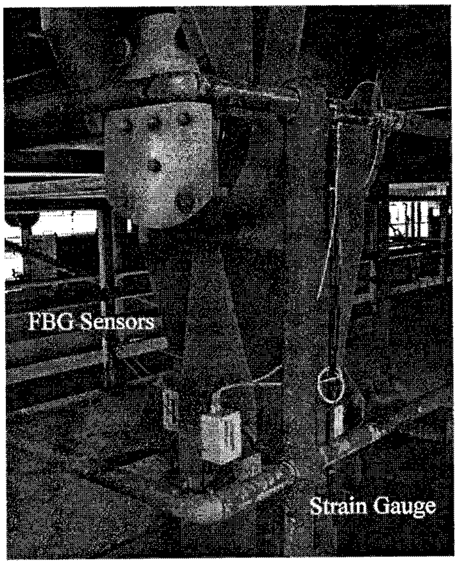


Figure 9 : FBG sensors installed beside an electrical strain gauge on a rocker bearing.

3.2.2 Suspension Cable Measurement

Six FBGs are mounted on the suspension cables. One of the FBGs mounted on a suspension cable close to the Ma Wan tower was monitored with the high-speed interrogation system. Via another input fiber, an athermal packaged FBG in a vibration-isolated case is used as reference. For the suspension cable measurement, the readout frequency is set to 0.106 ms. The results are shown in Figure 10.

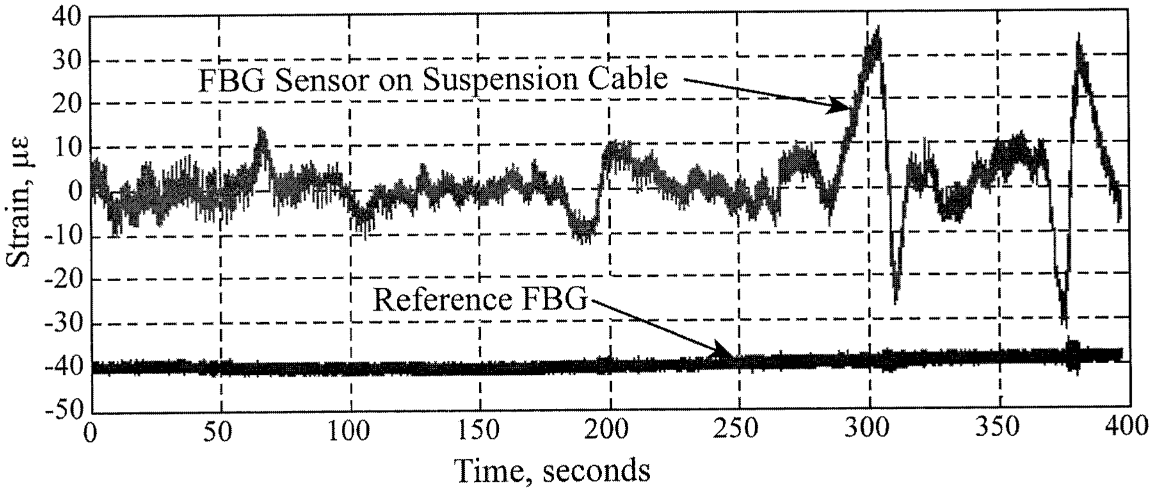


Figure 10: Suspension cable tension measurement. An arbitrary off-set of –40 μ ε is applied to the reference FBG.

Train passages at t = 307s and t = 377s can clearly be detected by the FBG mounted on the suspension cable. From the signal, we can also deduce that the trains are running in opposite direction. In the middle of the measurement, we noticed the passage of heavy traffic. This corresponds to the signal at t = 195s.

3.2.3 Rocker Bearings Measurement

Various measurements with the FBGs mounted on the rocker bearings (Figure 9) were performed including an overnight measurement of about 20 hours with a sampling time of 2.1 ms. The data of the strain gauges on the rocker were also logged. The results of a one-hour track are shown in Figure 11.

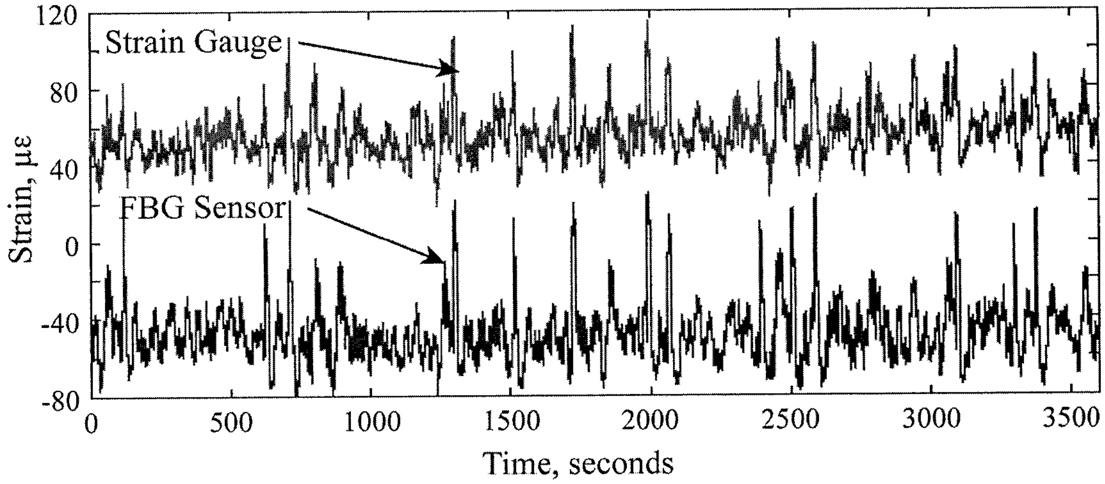


Figure 11: Comparison between FBG and conventional strain gauge on rocker.

In the TsingMa Bridge construction, the rocker bearings are used to support and hold the deck. Therefore, the loading on the rocker is very complex and the strain depends strongly on the position of the sensor. Despite the FBGs and the strain gauges are not mounted on the same location of the rocker. The signals of the 2 types of sensors, as shown in Figure 11, are found to be very similar and the train passages can clearly be detected.

3.2.3 Truss Girder Measurement

An array of 12 FBG sensors was mounted on different locations of Chainage 23 (Fig. 8). The FBGs are placed close to the existing strain gauges for an optimal comparison. In Fig. 12, the signal of a FBG is compared with the signal of the corresponding strain gauge. The sampling time of the FBG sensor is 0.0528ms. A moving average filter of 10 points is applied to the data of the FBG sensor and the detection bandwidth of the FBG sensor is reduced to about 2 kHz.

The FBG sensor signal has also an arbitrary offset for display purpose. Although the sensors are not located at exactly the same location, great resemblance has been found.

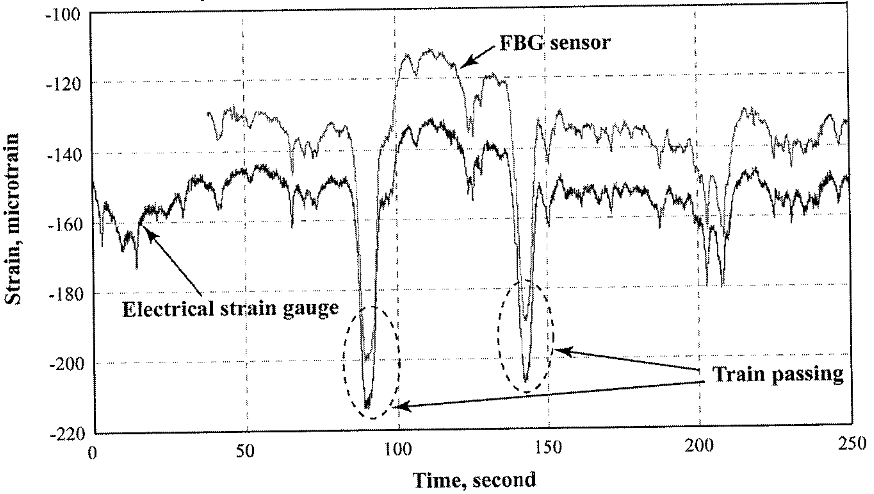


Figure 12 : Comparison between FBG strain sensor (upper trace) and strain gauge (lower trace) installed on frame of Section 23 of Tsing Ma Bridge.

4 CONCLUSIONS

Two field trials using FBG sensor arrays for train speed measurement and for strain measurements on different locations (suspension cable, rocker and truss girders) of the TsingMa Bridge were performed successfully. The result of using an FBG to measure the velocity of a train was presented. The FBG sensors can clearly detect train passages and due to their many inherent characteristics, their potential in the railway applications is very good. The measurement results of FBG sensors on suspension cable, rocker bearing and truss girders were also presented. Detail of the installation of the FBG sensors on the TsingMa Bridge was briefly described. The performance of FBG sensors was compared with the electrical strain gauges that were already installed on the TsingMa Bridge. Good agreement between these 2 types of sensors was obtained. However, it was also found that the installation of the FBG sensors was a lot simpler than the installation of electrical strain gauges.

Acknowledgements

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