CHAPTER 11

Fiber Bragg Grating Sensors for Railway Systems

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Abstract: Fiber Bragg Grating (FBG) sensor technology has been attracting substantial industrial interests for the last decade. FBG sensors have seen increasing acceptance and widespread use for structural sensing and health monitoring applications in composites, civil engineering, aerospace, marine, oil & gas, and smart structures. One transportation system that has been benefited tremendously from this technology is railways, where it is of the utmost importance to understand the structural and operating conditions of rails as well as that of freight and passenger service cars to ensure safe and reliable operation. Fiber-optic sensors, mostly in the form of FBGs, offer various important characteristics, such as EMI/RFI immunity, multiplexing capability, and very long-range interrogation (up to 230 km between FBGs and measurement unit), over the conventional electrical sensors for the distinctive operational conditions in railways. FBG sensors are unique from other types of fiber-optic sensors as the measured information is wavelength-encoded, which provides self-referencing and renders their signals less susceptible to intensity fluctuations. In addition, FBGs are reflective sensors that can be interrogated from either end, providing redundancy to FBG sensing networks. These two unique features are particularly important for the railway industry where safe and reliable operations are the major concerns. Furthermore, FBGs are very versatile and transducers based on FBGs can be designed to measure a wide range of parameters such as acceleration and inclination. Consequently, a single interrogator can deal with a large number of FBG sensors to measure a multitude of parameters at different locations that spans over a large area.

FBG is the most promising, cost-effective and distributed sensor technology that provides an ideal platform to monitor the condition and structural health of tracks, carriages and underframe equipment in railway systems. In the last few years, a number of field trial railway projects using FBG sensors for axle counting, track and train vibration measurements, monitoring of bogie conditions, structural health monitoring of train bodies, and interaction between overhead contact lines and current collectors (pantograph) were successfully conducted by a few research institutions. These studies demonstrated the superiority of FBG sensors over conventional sensors in many crucial aspects. However, major barriers, such as lack of proprietary and custom specifications, packaging and reliability standards, insufficient field experience, have yet to be resolved before major railway operators are to embrace the FBG sensor technology.

INTRODUCTION

The rail industry is enjoying its biggest development boom worldwide in recent years. Fuelled by growing trade and rising environmental concerns on road transportation, the United States invested nearly US$ 10 billion in 2008 and allocated US$ 8 billion for high-speed trains in 2009. Indian Railways will invest about US$ 50 billion under the 11th Five Year Plan to modernize its railway system. As part and parcel of China's rapid economic rise to become a modern nation, the scale of railway investment in China is gargantuan. In 2009, China spent US$ 50 billion on its high-speed rail system with a top speed of up to 350 km/hr. By 2020, China will have added more than 25,000 km of high-speed tracks and spend up to US$ 300 billion. Undoubtedly, the improvement of safety, reliability and productivity will continue to be the most important directive for the railway industry. This can be achieved through advances in on-board computers, on-board train condition monitoring systems, and wireless data transmission from wayside monitoring systems. There is also an increasing demand for better system reliability, availability, maintainability and safety from the communities. A smart condition monitoring system allows real-time and continuous monitoring of the structural and operational conditions of trains [1], overhead contact lines [2-3], 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, track and overhead contact line conditions to the 'intelligent systems' will herald a safer railway industry with reduced maintenance cost, optimized

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performance and capacity. Therefore, the need of a smart condition monitoring system is imminent as indicated by the increase in railway/underground accidents/incidences around the world. Smart condition monitoring systems for the railway industry would require extensive sensor networks with large number (1,000s') of multifunctional sensors for the measurements of temperature, strain/stress, vibration, acceleration, etc. Fiber Bragg grating sensors, in comparison to electrical sensors and other types of fiber-optic sensors, offer many advantages that are particularly well suited to railway transportation systems. These include immunity to EMI/RFI, long life-time (>20 years), and massive multiplexing capability – hundreds of sensing points along a single strand of optical fiber with length up to 230 km [4], fast measurement speed, self-referencing and inherent redundancy feature.

Quasi-distributed fiber-optic sensor based on fiber Bragg gratings (FBGs) is an excellent candidate for the realization of smart condition monitoring systems for the railway industry. There are more established distributed fiber-optic sensors based on Raman or Brillouin optical time-domain reflectometry but they are less suitable for condition and structural monitoring of railways which demand fast measurement time and high spatial resolution.

In this chapter, the important characteristics of distributed photonic sensors, potential applications for the railway industry and some field trials will be described. Some of the FBG sensor-based monitoring systems are fully operational and in present service use – are providing valuable 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 many other parameters relevant to railroad health monitoring and integrity.

DISTRIBUTED FIBER-OPTIC SENSOR TECHNOLOGIES

In distributed photonic sensor systems, a single fiber is used as the sensing element to substitute for thousands of conventional point sensors. The concept of distributed sensing was initially promoted in the late 70's by optical fibers based on Rayleigh back scattering mechanism and through the technique of optical time-domain reflectometry (OTDR) [5] for locating faults in optical fibers, up to 250 km with a resolution of ~3 meters.

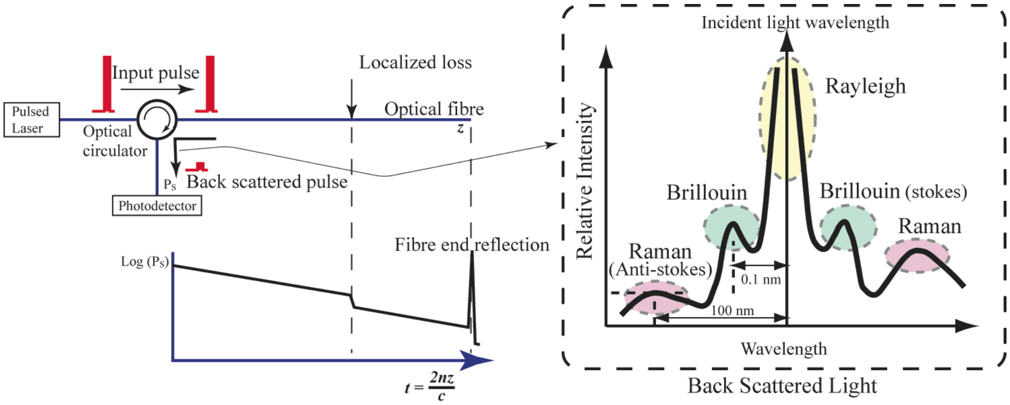


Figure 1: Principle of optical time-domain reflectometer for distributed measurement along an optical fiber.

(Fig. **1**) shows the basic configuration of an OTDR in which a short pulse (~10 ns) of light is launched into a test fiber. The back-scattered spectrum due to Rayleigh, Brillouin and Raman is also shown. The position of the measured quantity is computed via the time of flight of the backscattered light pulse propagating in the fiber. In the late 80's, a number of sensor configurations were proposed, mostly originated from the Raman and Brillouin scatterings in optical fibers [6-11]. Raman distributed sensing is based on the spontaneous scattering process generated by thermally-activated acoustic waves. Information about temperature is retrieved from the comparison between the intensities backscattered into the Stokes and the Anti-Stokes waves. Raman distributed sensor is now very mature and commercial units have typical performance of 1 K temperature accuracy with 1 m spatial resolution for fiber lengths up to 10 km. The measurement time varies from 1 minute to 10 minutes, depending on the required accuracy and spatial resolution. On the other hand, Brillouin OTDR does not base on intensity measurement, but the frequency shift of the Brillouin scattered wave. The Brillouin frequency shift depends on both temperature and strain, and the backscattered power depends solely on temperature. Brillouin OTDR can thus be used to measure temperature and strain simultaneously.

Commercial Brillouin OTDR has the capability of measuring distributed strain and temperature with a resolution of 20 με and 1 K respectively, and with 1 m spatial resolution over a distance of 30 km in 1 minute. Distributed photonic sensors based on Raman and Brillouin OTDRs offer many advantages over conventional sensors in applications where a large number of sensing points is required and the environment is hazardous. In addition, optical fibers are non-conductive, non-corrosive, unaffected by EMI and RFI, low loss and small size. A common application of Raman OTDR is in the measurement and identification of hot spots along power transmission lines. Brillouin OTDRs are being employed in locating leaks in oil-pipe lines. However, the Raman and Brillouin distributed sensing systems require long measurement time and generally exhibit spatial resolution of the order of meter. Consequently, they are not suitable for applications where fast response time is needed or the required sensing regions are small.

On the contrary, fiber Bragg grating sensors [12-13] can be interrogated at very high-speed of up to 2.5 Msamples/s [14]. FBGs are very small – short length of single-mode fiber (down to 0.1 mm) with periodic refractive-index variation in its 9-μm core, as shown in (Fig. **2a**). FBGs can be created to reflect narrow-bands of spectrum (typically <0.2 nm) at virtually any wavelength. Consequently, many gratings with different reflection wavelengths can be fabricated on a single strand of optical fiber. The fabrication of long-period gratings (LPGs) with period of several hundreds of microns is shown in (Fig. **2b**). LPGs operate in transmission mode and could be employed as low-cost optical filters or sensors. They are, however, very sensitive to environmental perturbation and therefore not as popular as FBGs.

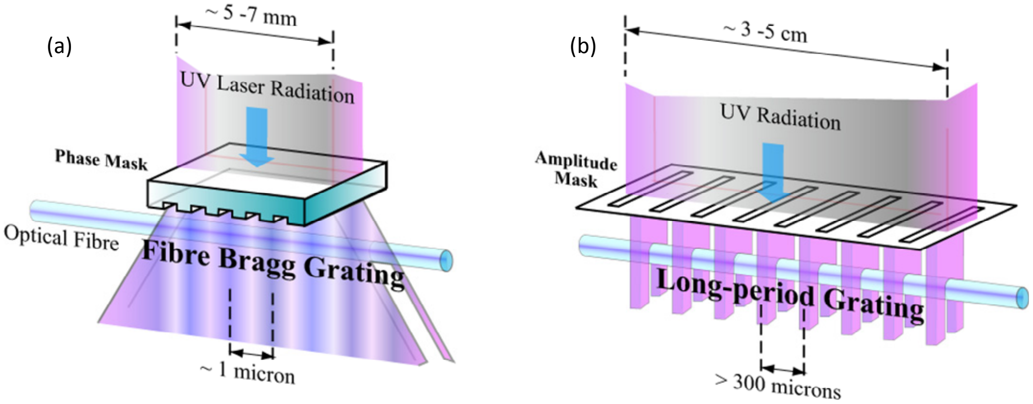


Figure 2: Schematic diagrams of the common techniques employed for the fabrication of (a) fiber Bragg grating using phase mask and (b) long-period grating using metal amplitude mask.

FIBER BRAGG GRATING SENSOR TECHNOLOGY

Fiber Bragg grating sensors are normally fabricated in standard telecommunication optical fibers using either an interferometric technique or phase mask technique (shown in (Fig. **2a**) to create an interference patterns in the fiber core with an UV laser beam. The latter technique is easier and thus more commonly used. More information on the fabrication and interrogation of FBGs are given in other chapters of this book. Typical cost of standard fiber is about US$ 10/km and therefore the material cost of an FBG is very inexpensive. The majority of the cost of an FBG sensor system comes from the sensor packaging and the interrogator. The reflection/Bragg wavelength of FBGs created in standard optical fibers exhibit wavelength-shift of 10 pm/K and 1 pm/με around 1550 nm. Consequently, FBGs are employed to measure temperature and strain by determining the reflection wavelength of an FBG. Many schemes to discriminate strain and temperature or to measure both parameters simultaneously using FBG sensors have been derived [15-21]. The simplest and practical scheme is to use two FBGs with one of them for measuring temperature unattached but in close proximity to the structure where strain is to be measured. In additional to the intrinsic advantages of optical sensors over electrical sensors, such as EMI/RFI immunity, non-electrical conductive, FBG sensor technology exhibits many advantages that are particularly suitable for railway applications. The important features of FBG sensor technology for railway transportation systems are:

- **Entirely passive sensors**

  Unlike most electrical sensors, FBG sensors do not require any power to operate and therefore no active electronic circuitry is required within the measuring objects. Consequently, trackside equipment susceptible to EMI/RFI is not needed in FBG sensor networks. This is important because it reduces the cost as well as the downtime of the sensor systems.

- **Multiplexing capability**

  Unlike truly distributed sensors such as Raman- and Brillouin- OTDR where the entire optical fiber is used to measure temperature or strain, only sections of an optical fiber where FBGs are inscribed are sensitive to strain/temperature. In railway applications, truly distributed sensing is rarely required and FBG sensor systems allow the critical points of a railway system to be measured quickly and accurately. The multiplexing capability of large number of FBGs on a single optical fiber simplify sensor installation and also make the sensor system cost-effective in railways where large number of sensing points are needed.

- **Multi-functionality sensing**

  FBGs are very small, they function like strain gauges but are operated optically. FBG-based transducers for measuring parameters other than temperature and strain can be realized, allowing one FBG-interrogator to measure many parameters such as acceleration [22-24], E-field [25], B-field [26], and tilt angles [27-28]. Therefore, a single FBG sensor network could replace a multitude of conventional electrical sensor systems employed in railway industry.

- **Ultra-long reach sensing**

  The exceptionally low-loss of standard telecommunication fibers permits light around 1550 nm wavelength travel to and from FBG sensors over 100 km. The distance between the FBGs and the interrogator is limited by Rayleigh scattering noise to about 25 km and it is extensible to 50 km by introducing distributed Raman amplification to the connecting fibers [29-30]. The distance can be further extended to 230 km by switching on and off the interrogating wavelength-tunable laser to reduce the Rayleigh scattering noise [4]. Other schemes for improving the signal-to-noise ratio and dynamic range of ultra-long reach FBG sensor systems were also demonstrated [31-32]. A single FBG-interrogator therefore has the capability to monitor rail tracks up to 230 km long without the need of any trackside equipment.

- **Redundancy**

  Redundancy is essential in railway industry to provide safety, reliability and quality of service. Redundancy in FBG sensor systems is relatively inexpensive and easy to implement because of the reflective property of the FBGs and the fact that a single FBG-interrogator can handle many FBGs for measuring many difference parameters over ultra-long distances. The reflection wavelength of an FBG can be measured from either end. Furthermore, a single FBG interrogator with the unique capability of handling many FBGs to measure various kinds of parameters makes redundancy implementation easy and relatively inexpensive.

- **Uniquely identifiable sensors**

  Wavelength-division multiplexing (WDM) technique is commonly used to demultiplex FBG sensors along a single optical fiber. In WDM sensor system, each FBG along a single optical fiber is uniquely identifiable by its reflection wavelength as no two FBGs occupy the same wavelength slot at any time. This feature greatly reduces the risk of mistaking the mesaurands obtained from the FBG sensors along an optical fiber and lowers the sensor system downtime. The uniquely identifiable FBGs along a fiber require neither re-calibration nor re-initialization, further reducing system downtime.

- **Large usable wavelength range**

  FBGs are normally inscribed in standard singlemode telecommunication optical fiber which has a cut-off wavelength around 1250 nm and thus they operate in singlemode for wavelength range from ~1250 to

~1650 nm, spanning the entire O-, E-, S-, C- and L-bands as defined in optical communication WDM systems. A single fiber has a large usable wavelength range to support many FBG sensors. Time-division multiplexing technique (TDM) permits the use of FBGs with identical wavelength. The combination of TDM and WDM techniques allows a single optical fiber to measure several hundreds of locations [33]. The main disadvantage of the TDM approach is the small signal-to-noise ratio compare to that of WDM technique and consequently TDM of FBG arrays is not common.

- **Wavelength-encoded measurands**

  Temperature, strain and vibration measured with FBGs are encoded in the wavelength-shift of the reflection spectrum. Wavelength is an absolute parameter, the measured signals is therefore not loss-affected. Unlike most conventional sensors, loss fluctuations in FBG sensor systems do not affect the measurement so long as sufficient power reaches the FBG-interrogator. This feature minimizes noise and significantly enhances signal integrity of the measurements by FBG sensors.

An FBG sensor network configuration with redundancy to deal with possible sensor fiber breaks and interrogator failures can be easily implemented because of the many unique features of FBGs aforementioned. (Fig. **3**) shows an FBG sensor configuration in which the far ends of all the FBG sensor fibers are connected back to the FBG-interrogator via 2×2 solid-state optical switches which exhibit much higher reliability and longer lifetime than mechanical switches.

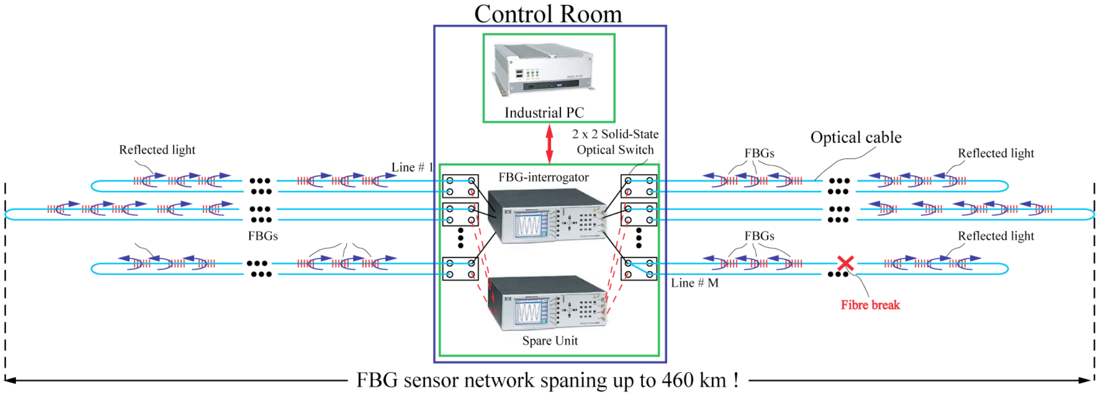
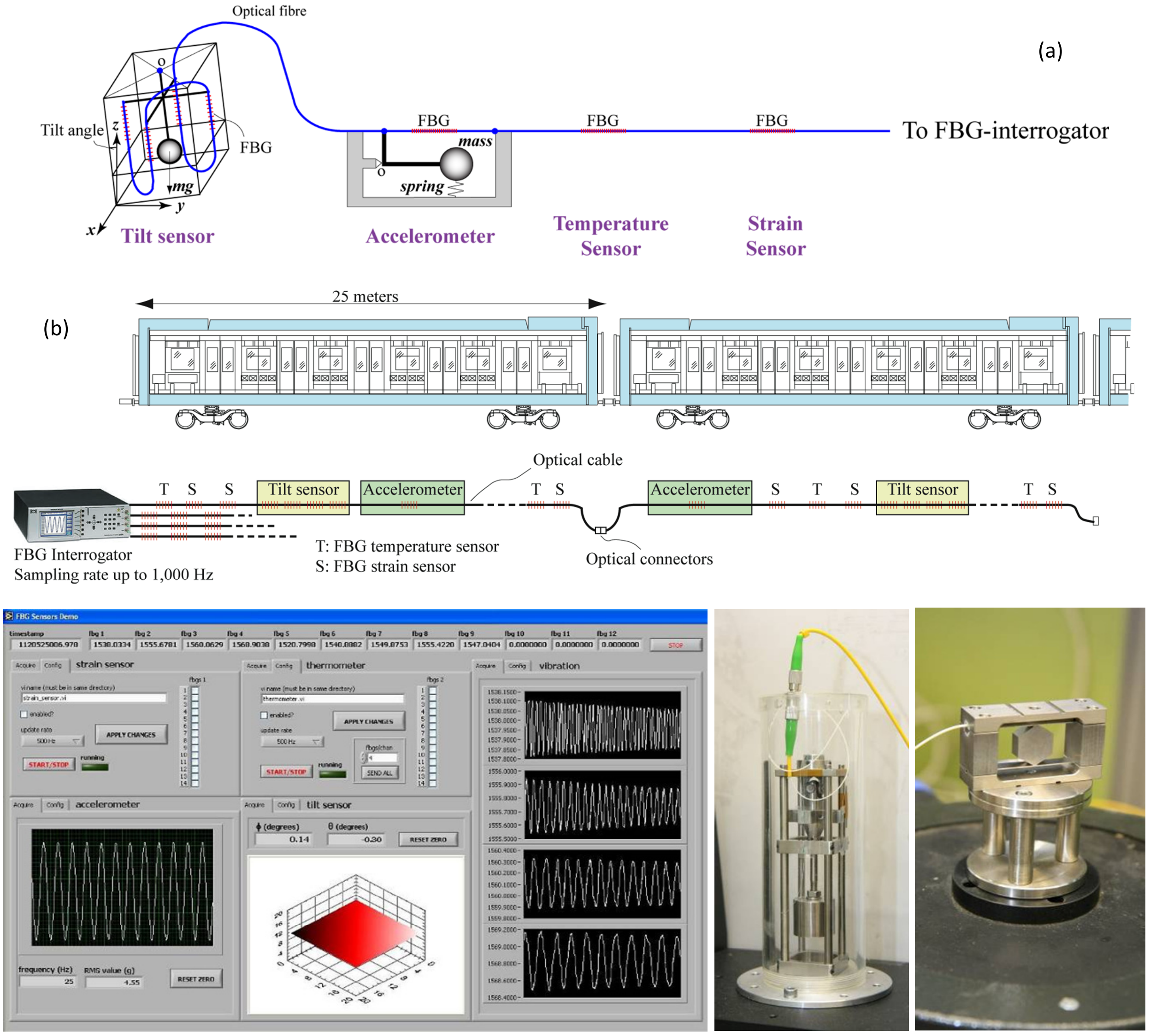


Figure 3: An FBG sensor network covering up to 460 km of rail tracks with hundreds of sensing points with redundancy in fiber links and FBG-interrogator.

In normal operation, only one output of the optical switches is connected. In case there is a break in the sensing fiber, for example, in Line # M of (Fig. **3**), all the FBG sensors in Line # M can still be interrogated by switching the input of the optical switch to its two outputs, alternatively. The second inputs of all the optical switches are connected to a spare FBG-interrogator in case the first FBG-interrogator break down. (Fig. **4a**) shows the use of 7 FBGs, along a single optical fiber, to measure strain, temperature, acceleration, and tilt angle. (Fig. **4b**) depicts that many FBGs for measuring different parameters of a train can be integrated by a single sensor system with one FBG interrogator – substantially simplifying installation, rendering a cost-effective sensing system and thus providing a unified sensing solution to railway industry. (Fig. **4c**) demonstrates the user interface of an FBG sensor array for displaying the results of acceleration, tile angle, strain, temperature and vibration, obtained with one FBG-interrogator. The photographs show an FBG-based inclinometer [27] and FBG-based accelerometer.

APPLICATIONS OF FBG SENSOR ARRAYS IN RAILWAYS

In railway systems, the smooth operation of trains necessitates proper designs and integration of trains and tracks. Since a train-on-track system is a highly complex integration of various engineering entities while operational and environmental factors may vary significantly from one system to another, railway engineers rely on not just fundamental engineering knowledge alone but also their experience and on-site data to achieve high quality train services. In short, the quality of train service includes general safety of the rolling stock, reliability and availability of services, payload stability and passenger comfort. There are numerous factors among trains and tracks affecting the overall quality of train service. Some of these factors are recessive but are of vital importance.



(c) FBG sensor interface Inclinometer Accelerometer

Figure 4: Multi-functionality of FBG sensors for the measurement of temperature, strain, tilt angle, and acceleration of train wagons using one FBG interrogator.

For trains, the wheels are the frontline components in contact with the track and the condition of wheels is determinative to train operation safety and ride comfort. Out-of-round wheels, wheel flats, spalling, pitting and distorted wheel profiles are common problems that can be found on train wheels. Impaired wheels lead to excessive vibration and low adhesion to track or even flange-climb which in turn may result in derailment. Powering the next generation of trains will be more demanding because of the higher speed; and more power will be required to support the increasing number of electrical amenities inside the trains. It is therefore crucial to monitor the temperature and contact force [2-3] of the overhead line to ensure reliable electrical supply. Other moving parts on bogies, such as axle bearings, motor and gearbox bearings, brake mechanisms, primary and secondary suspension systems, are prone to malfunctions due to tear-and-wear, over-stress, under-maintenance or even improper installation. Overheat at axle bearings may arise when they are run dry or operated under excessive vibration of the wheels. Moreover, brake and suspension jams are not uncommon and they may lead to catastrophic derailment and train collision. Apart from the moving parts, structural components of a train may have problem from time to time. Train structures, such as sole bar, body shell, equipment brackets and the corresponding weld joints, are the most susceptible components. When a train is running on track, the train structures are subject to multi-dimensional forces which lead to train structure deformation and fatigue. For example, shearing and torsion stress are the two main forces experienced by the train body which can result in torsion distortion of the body shell, door jam and window shatter. When a train roll, pitch, or yaw as it runs on track, underframe equipments, which are essentially swing masses hanging beneath the train body, are imposing dynamic stresses accumulatively to the equipment brackets. As a result, metal fatigue is developed at high stress points such as weld joints. Although the lifetime of these structural components are comparatively long and some of them are even lifetime guaranteed, damages can still be observed occasionally. Any deformation or breakage of these structural parts can do the same harm to the railway as a broken moving part.

Rail tracks in railway systems are comparatively passive and only limited active components are attached to them. The principle functions of rail tracks are to support and to guide the rolling stocks running on them. In additional to the point and cross devices, rail tracks are equipped with train detection and signaling equipment which are essential to train operation. Rail tracks can suffer from mechanical problems similar to train wheels, such as head checking, spalling and peeling, which are caused by rolling contact fatigue. The supporting components of rail tracks, sleepers and ballast, may also deteriorate with continual train operation. Rail track problems are usually difficult to identify at its beginning and it may very soon develop into bigger problems, like rail cracks.

Nowadays, even though track equipment is embedded with features to ensure safe train operation, there is no proven means to monitor the train-to-track interaction and the condition of rail tracks. Rail track is usually inspected routinely or on request which is done either by portable flaw locator or automatic ultrasonic flaw detector vehicle. Due to operational constraints, a section of rail track can only be inspected once every few weeks or months. For trains, the practice is very much the same and trains are maintained on a specific schedule or on request. Railway engineers have encountered numerous problems in installing permanent online sensing systems on trains and tracks using conventional sensors. For example, as most of the modern railways are electrically powered, all sensors installed on track or outside the train body shell are vulnerable to high electric field and EMI. Conventional electrical sensors must be heavily shielded in order to achieve acceptably low noise level but this inevitably increases the size of the sensing system, which is not desirable for condition monitoring for neither trains nor tracks. Further, as the signals of most electrical sensors are weak, amplifiers and data loggers must be installed in the vicinity of the sensors. For rail tracks over tens or even hundreds of kilometers, this topology is impractical and even for trains, there is no such space for the instrumentation and cabling. For these reasons, sensors are only installed on trains and tracks during the commissioning stage or for the investigation of certain incidents and the tests must be carried out in non-servicing hours or with non-servicing cars. More often than not, a minor problem on train or track does not induce sufficiently perceptible disturbances to the driver or passengers to raise the alarm for maintenance. Consequently, in the absence of online sensing systems to monitor the conditions of trains and tracks, it is very likely that minor problems are being unattended for weeks or months and the resulting damages and repairs are usually costly.

In railway systems with heavy traffic loading, such as the metro lines in highly populated cities, minor damages on trains and tracks can develop into more severe incidents within a very short period of time. A real-time monitoring system capable of monitoring train-to-track interaction is indeed an effective means to avoid derailment and accidents. For example, the Eschede high speed train disaster [34] occurred in 1998 near the village of Eschede in the Celle district of Lower Saxony, Germany, could have been avoided if a real-time monitoring system were installed and the train operator were given early warning. The tragedy involved derailment of a high speed train, with heavy casualty and a 300-tonne overpass at the railway being knocked down. The Intercity Express (ICE) high speed train was installed with noise suppressing wheels employing steel tires and rubber laminations. The steel tire was excessively worn out and eventually it lost its strength. The deformed steel tire soon resulted in cracks which caused the tire to fracture during the high-speed operation. The tire peeled off from the wheel and punctured the train which started to wobble on the rail track and triggered a series of damages to the track and train. Consequently, the third car was thrown into the piers supporting a 300-tonne roadway overpass and the subsequent cars were jackknifed into the rubble. It was evident that the steel tire penetration to the train was reported to the train crew aboard but it still took minutes to determine if the emergency brakes had to be applied. In fact, it was just too late to communicate and verify the incident. From the train operation point of view, this accident is avoidable by monitoring the real-time conditions of the trains and the train-track interaction. Abnormal train-track interaction due to the over-damaged wheel should have been detected and the driver would have been made aware of the problem and given time to stop the train.

In the future, the railway systems will certainly incorporate more high speed lines with increasing traffic demands, problems in trains and tracks will occur more frequently and they need to be attended to and rectified as soon as possible. Obviously, the conventional practice for flaw detection and maintenance is inadequate and there is an urgent need of a practical online monitoring system to report and record the status of trains and tracks. Being versatile, small in size and immune to EMI/RFI, FBG sensors have found their places in railway applications.

Railway Applications

Train Status
- online monitoring of train components (e.g. body shell, solebar, weld joints, equipments)
- evaluation of train structure integrity
- act as track condition monitoring car

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

FBG Interrogation System

Axle counting & Train Vibration
- high performance axle counting system to ensure the same number of cars entering and leaving a block for safe train operation
- train vibration monitoring to assist train operator to identify defective trains

Motor Health
- early motor fatique prevention
- localized heat spot identification
- monitor motor bearings condition

Pantograph & HV Line
- capable to monitor high voltage zone not accessible by electrical sensors
- online measurement of contact force on pantograph to improve life time of contact line and pantograph

Critical Moving Parts
- continuous and online monitoring of bogie parts
- earlier fault detection to reduce damage
- access to difficult location with high EMI

Axle Load Evaulation
- assess train to track adhesion and axle load imbalance to avoid derailment
- payload and passenger estimation for overload prevention

Figure 5: Many railway applications currently monitored using various conventional electrical sensor systems as shown in the figure could be replaced with FBG sensor technology.

Recently, substantial amount of researches and field tests have been successfully conducted on applying FBG sensors in railway operations, including train and track condition monitoring [35-36], train identification [37-38], train speed and weight measurement [39] and axle counting [40-41]. A practical FBG based railway monitoring system has been demonstrated, in which FBG sensors are used for temperature and strain measurements on train wagons, bogies and rail tracks in the development of a "Smart Railway Sensor Network" by incorporating optical sensory nerves at various parts of the railway networks. The "optical nerves" can be further extended to monitor other railway installations or equipment, such as transformers and overhead power lines. The work reported in Refs. [1, 35, 37-40, 42] involved the development and implementation of several optical fiber distributed sensor systems that incorporate hundreds of FBG in five trains and five track sections covering all forms of mid-life refurbishment trains and suburban line tracks. The FBG sensing systems installed on trains and tracks work together as a train and track monitoring system. FBG sensors installed on the trains measure and record the strain, vibration and temperature of the train components onboard and they also scan the entire rail track during revenue services.

Likewise, the FBG sensors installed on tracks monitor both the tracks and the passing rolling stocks. The studies with the rail operators have demonstrated that the application of FBG sensors in the railway system have the potential to revolutionize condition monitoring in the railway industry and to upgrade the conventional systems into 'Smart Railways', thereby providing safe, reliable and vital information to railway operators. The FBG sensors can be used to build up many important railway sub-systems, such as axle counters, derailment monitors, train load detectors, as well as continuous rail crack detectors to permit real-time monitoring of the entire rail network, allowing maximization of network capacity, optimisation of electricity utilisation and effective detection of potential operational hazards and thus enhancing the overall service safety and quality. (Fig. **5**) shows the various conventional electrical sensors in railway that can be replace with FBG sensor technology.

FBG Track-Based Wheel-Rail Interaction Sensing Systems

The safety, operating performance, and ride quality of railway system rely on the interactions between the wheels and the rail tracks. Measurements on the wheel-rail interaction provide critical information on the condition of the rails and the trains running on them. When an axle passing on a rail track, the forces at the wheel-rail interface can be monitored with FBGs attached to the rail foot.

In order to ensure the most sensitive measurement of strain change on the rail, it is necessary to analyze the momentary deformation of the rail due to a passing wheel. The Ansys Multiphysics™ software has been employed to simulate the levels of rail deformation when a train is standing by the rail. The rail model UIC54 is adopted in the simulation. It is made of steel, with a Young's modulus of 207 GPa and a Poisson ratio 0.29. Under the weight of a static train car of 48 tones, supported by 8 wheels, the maximum deformation of the track is found at its head of the rail where the train wheel stands, and the second highest deformation is at the rail foot, as shown in (Fig. **6**). In the longitudinal direction, the deformation is reduced as one moves farther away from the contact point. In the vertical direction, the rail web suffers from the least deformation, and both the rail head and foot are experiencing high deformation.

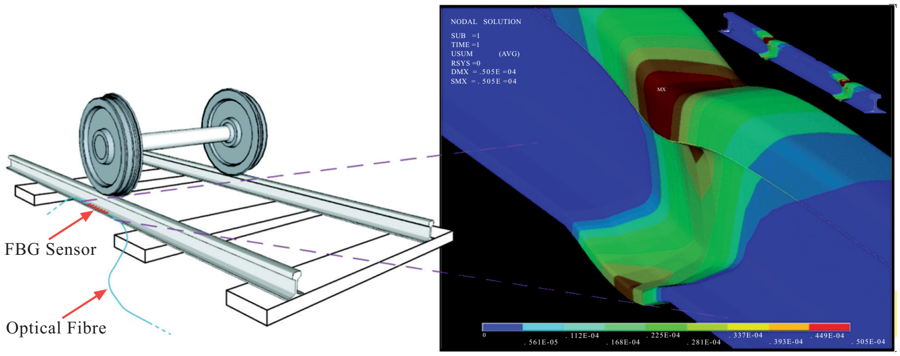


Figure 6: Simulation of stress distribution on a rail track due to the passing of a train.

The simulated stress distribution result indicates that there is region of sufficiently large area of relatively uniform stress region on the rail foot where FBG can be attached without suffering from significant chirping that broadens the reflection spectrum of the FBG and leads to inaccurate measurements. The FBG sensors are epoxied on the rail tracks and are connected by outdoor optical cables to a multi-core optical fiber backbone cable. (Fig. **7**) shows a typical strain measurement result obtained from an FBG attached on a rail track when a train consisting of 12 cars in the “T-M-T = T-M-T = T-M-T = T-M-T” configuration was passing over it, where T and M represent the trailer and motor cars respectively.

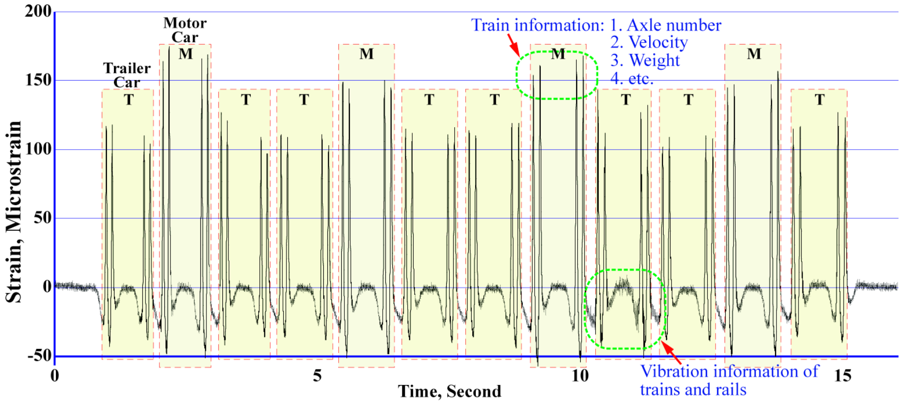


Figure 7: Measured induced strain due to a 12-wagon passenger train passed over a rail.

The results shown in (Fig. **7**) give important and vital information related to the structural and operating conditions of the trains and rails. It is quite amazing that a single 6-mm long FBG sensor attached onto a rail is providing such a multitude of important information with very good signal-to-noise ratio. The occurrence of a peak strain represents an axle; the actual strain-peak conveys the wagon’s weight; and the vibration of the train/rail can be extracted from the high-frequency components. The motor car is generally heavier than a trailer car because it also carries two motors and therefore the measured strain of motor cars shown in the figure is higher than that of trailer cars. Conventional axle counter consists of a pair of electromagnetic coils mounted on either side of the rail head as shown in (Fig. **8a**), one being the transmitter and the other the receiver. A magnetic field is established between the two coils. When a train wheel is running on the rail and between the coils, the magnetic field is so distorted that the induced voltage on the receiving coil changes direction, which registers the passage of one wheel. Two sets of axle counters are installed at the two ends of a signaling block; and a comparison of wheel passage count of the two axle counters verifies whether there is train occupancy in the block (when the axle counts of the two counters are different) or whether the train has moved away from the block (when the axle counts of the two counters are the same). However, as the operation hinges on the delicate changes of magnetic field, EMI remains to be a genuine concern for the reliable operation of axle counters. (Fig. **8b**) shows a fiber-optics version of axle counter realized by FBG sensors. The advantages and attractiveness of the FBG-based axle counter over the conventional approach is quite obvious from the figures. It has to be reiterated that FBG sensors allow the operators to get around the main disadvantages of the conventional electrical train detection methods, such as the need of expensive trackside equipment, reliability and maintainability concerns, susceptibility to EMI, and traction return current interferences.

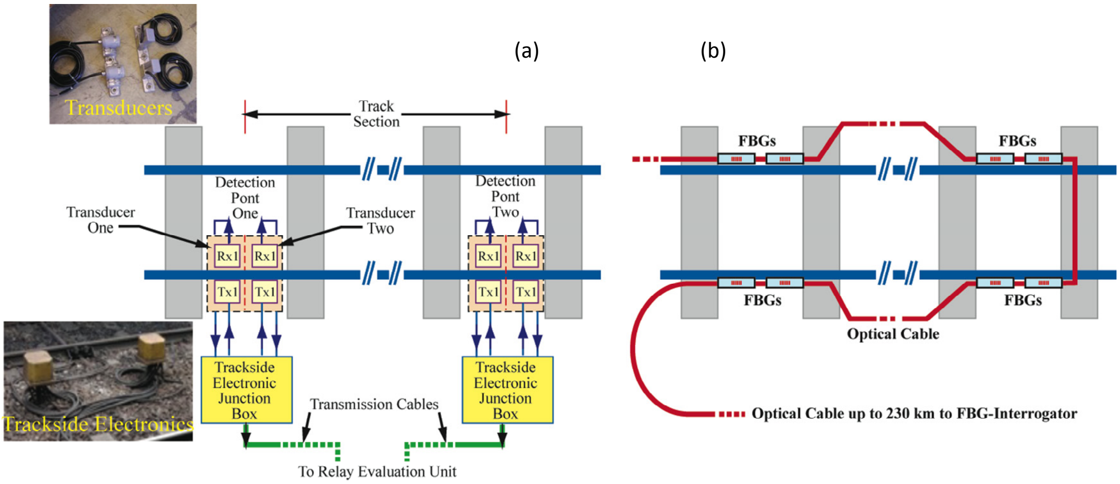
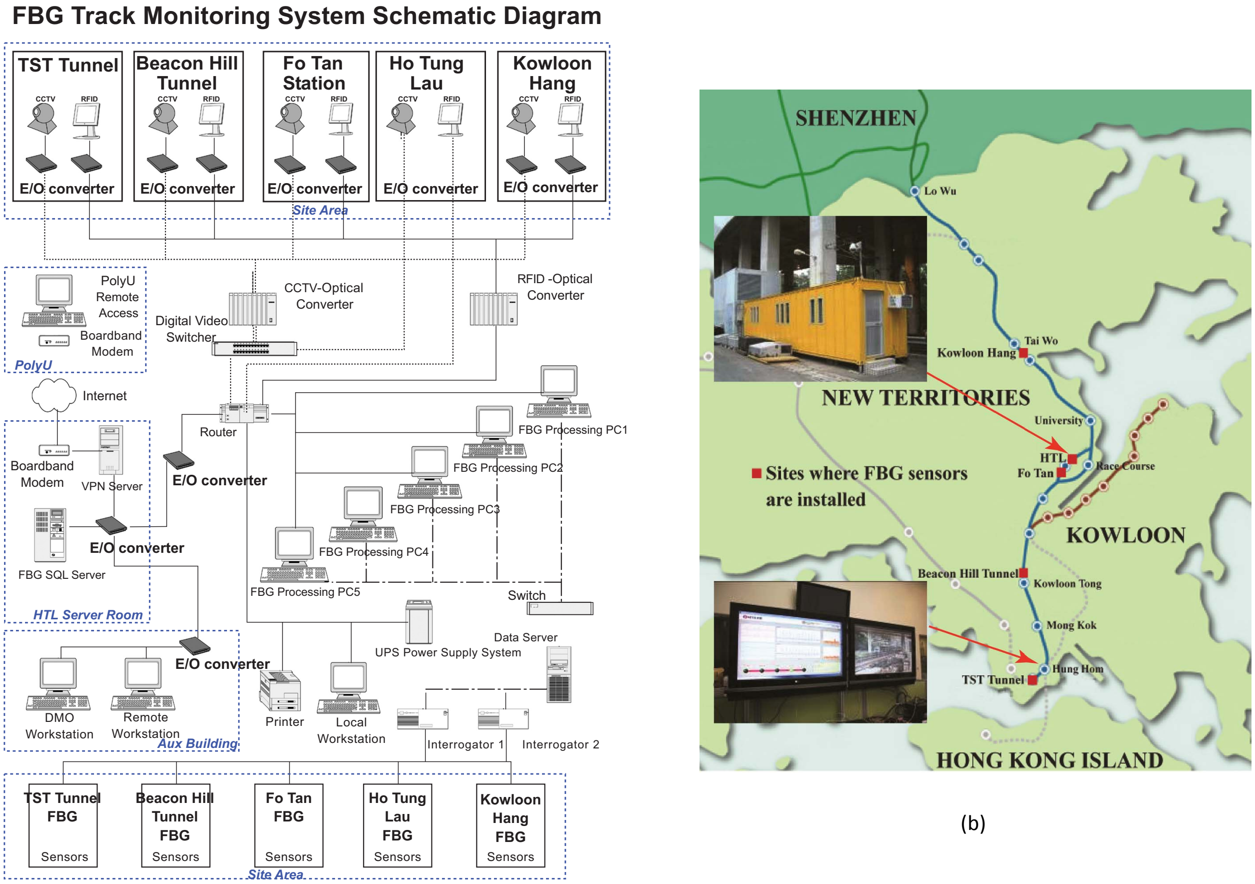


Figure 8: (a) Conventional axle counters and (b) Fiber-optic FBG-based ‘axle counter’.

(Fig. **9a**) shows the installation of the track based train monitoring system at the five sites along the Hong Kong East Rail which is a part of the "Smart Railway Network" reported in Ref. [1]. The East Rail is about 36 km long and covering 14 stations from Tsim Sha Tsui (TST) to Lo Wo (Fig. **9b**). The sites are equipped with CCTV cameras and RFID readers to record the ID of the passing electric multiple units (EMU). Each site is also installed with about 10 FBG sensors on the rail tracks to measure the strain induced on the tracks by the passing trains. The RFID data and CCTV camera are also connected to the same optical fiber cable after electro-optical conversion. All FBG sensors are ultimately connected to a FBG interrogator located in a satellite laboratory at the maintenance depot (HTL) at which the FBGs are interrogated at up to 1,000 samples/s. In case of a failure in the primary FBG interrogator, the system will switch to a backup interrogator installed at the same site for instantaneous service resumption. FBG data are manipulated by processing computers at the HTL laboratory and the FBG sensors are traced back to the wagons by their IDs.



(a) (b)

Figure 9: (a) Schematic of FBG rail track monitoring system and (b) Locations of the five sites where FBG sensors are installed [1].

(Fig. **10**) shows the typical measured result of an FBG installed on a 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 με and the noise is less than 5 με, giving a SNR of better than 17 dB. For comparison, a typical received signal from a conventional magnetic axle counter is also shown in the inset of (Fig. **7**). It is evident that signals attained from the FBG system are substantially cleaner than those from the conventional axle counter. 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 rail track, separated by a known distance can also be used to measure train speed. 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. FBG sensors on rail tracks are thus be used as axle counters and at the same time they provide important information for speed and weight measurements.

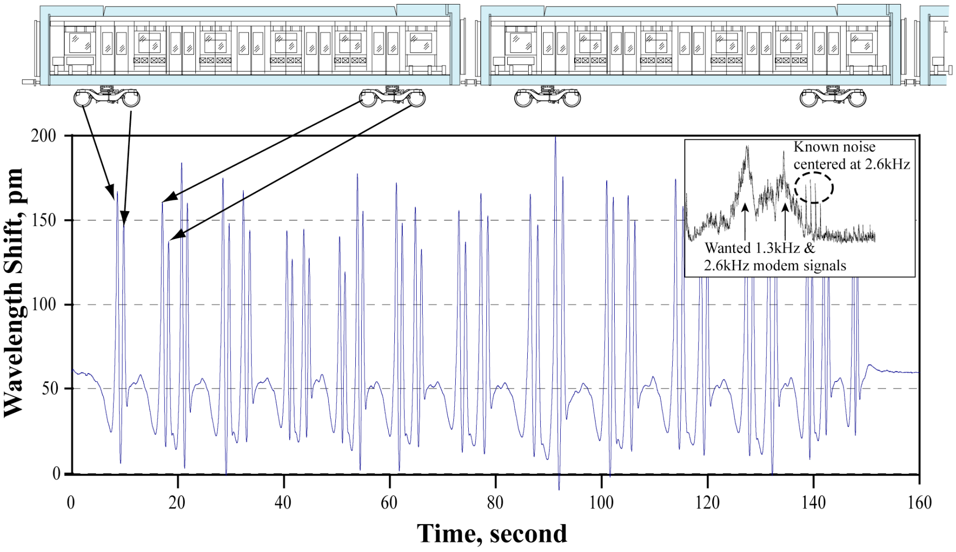


Figure 10: Measurement results of FBG sensors for counting train axle. Inset shows the received signal from a conventional magnetic axle counter after transmitted through a copper cable.

(Fig. **11**) shows the track-based FBG sensing system reported in Ref. [38], identifying a train with excessive vibration due to damaged wheels. Damaged wheel produces abnormal vibration patterns which are observed in between the axle signals (Fig. **11a**). In order to quantify the vibration strength and make it more indicative to train operators, an algorithm was developed to convert the vibration signal to a pre-defined numerical index.

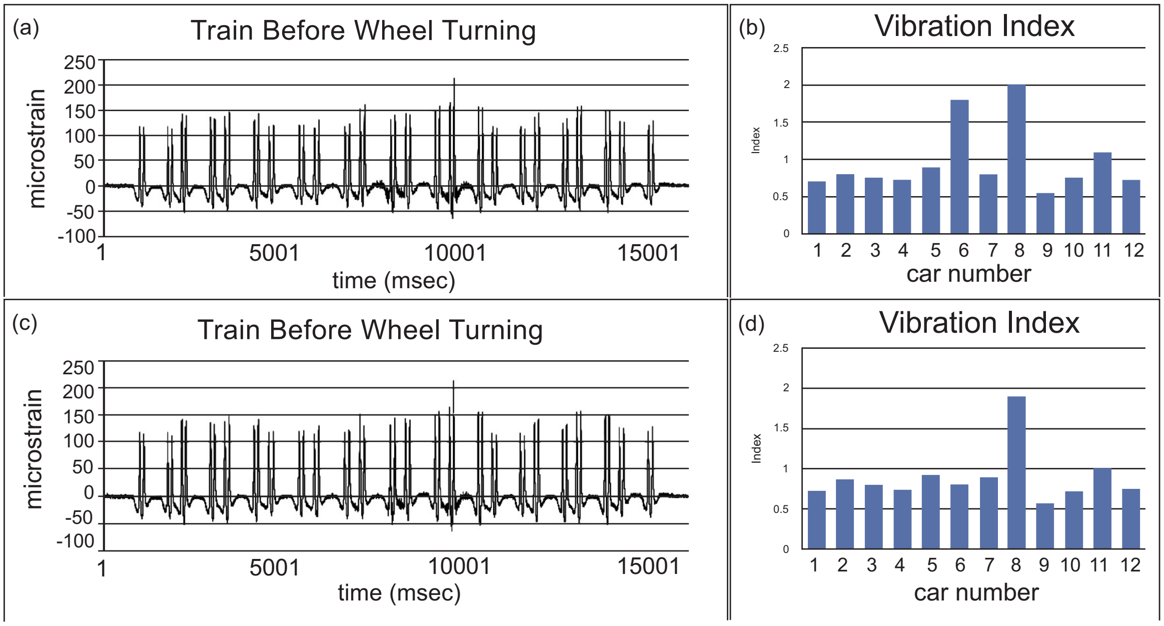


Figure 11: Identification of train with excessive vibrations.

In this demonstration, the 6th and 8th cars of the train are vibration prone they are spotted by the high vibration index (Fig. **11b**). The performance of the system is then evaluated by having the maintenance work on the wheels of the 6th car but not those of the 8th car. From (Fig. **11c**), it can be observed that the vibration pattern and index (Fig. **11d**) of the 6th car returns to normal after maintenance but condition of the 8th car remains. For practical reason, the system was designed with certain features to help the train operator in a number of ways. For example, alarm levels for the vibration index are preset to the system in such a way that it refers automatically to the data of a problematic train on a separate database. The workload of the operator is thus reduced. Besides, different warning levels are set to indicate the urgency of the maintenance need. For example, intermediate alarm level may stand for maintenance booking for the train while a substantially high alarm may represent an emergency maintenance. Since the dynamic behavior of trains may differ from one to another, the system measures and records the vibration patterns of all trains and produces database for each individual train. Based on these records, the system keeps tracks of the wearing rates of wheels which help the operator to identify abnormality among the trains. FBG sensors can also be installed on the two rails of a track to detect imbalances of axle loads on a track. It is well known that if there is significant difference between the left and right hand side loading of an axle, the danger of derailment rises. Thus, freight trains are required to go through a wheel weighing system. This system consists of strain gauges and load cells installed on a specifically designed resilient track. The wagon to be weighed must stop over the weighing system or run at low speed (<5 km) to obtain correct result. The reliability and stability of the system is low as strain gauges and load cells are vulnerable to EMI, lightning strikes and flooding. Besides, the accuracy of the system is sensitive to the condition of the resilient track which is frequently affected by mud during raining seasons. Thus, the overall reliability and efficient of the weighing system for axle load imbalance detection is low. On the other hand, FBG sensor can perform much better at the track side and also easier to install and maintain. A high performance axle load determination and derailment prevention system can be built using FBG sensors as the basic sensing components.

Monitoring of Dynamic Strain at Weld Joints for Mounting Underframe Equipment

Train underframe equipment, such as transformers, alternator and main equipment case, are sizable and heavy and any fall-off of underframe equipment will lead to severe damage to the train or derailment. Although train structures are designed to be durable and almost maintenance free cracks in underframe equipment brackets are still reported [38]. In this study, the stress levels at the various major equipment brackets are investigated and one single FBG sensor system is installed in each of the four typical train models that were used in the suburban line. FBG sensors are attached to the weld joints of the mounting brackets at which the stress levels are the highest. The FBG sensors are interrogated by an FBG interrogation system installed onboard which also log the train signals such as train speed, door signals and train direction, etc. (Fig. **12**) shows the locations of underframe weld joints at which FBG sensors are installed. (Fig. **13**) shows the typical dynamic strain results obtain from the weld joints.

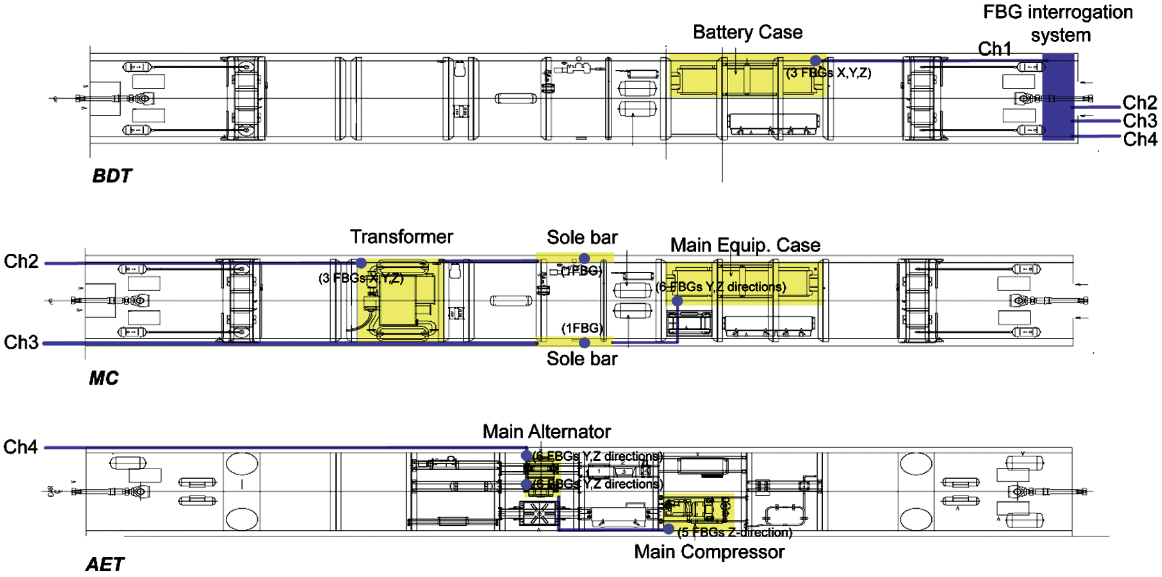


Figure 12: Locations of weld joints where FBG sensors are installed for monitoring the dynamic strain of the joints where heavy critical under-frame equipment are mounted. BDT = Battery Trailer, MC = Motor Car, AET = Auxiliary Equipment Trailer [38].

In order to investigate the conditions of the weld joints and to evaluate their actual life times, the cyclic stresses of each of the weld joints were recorded during train normal services. The accumulative effects of the cyclic stresses are quantified into an index. By referring to the recommendations in BS7608, the life times of the weld joints are then projected. The train vibration profile is matched to the corresponding track section by making use the train speed and door signals to identify the trips. Thus, in case high stress level is recorded repetitively at particular weld joints or particular sections of track exhibit high perturbation to trains, remedial works are carried out to avoid further deterioration at trains and tracks.

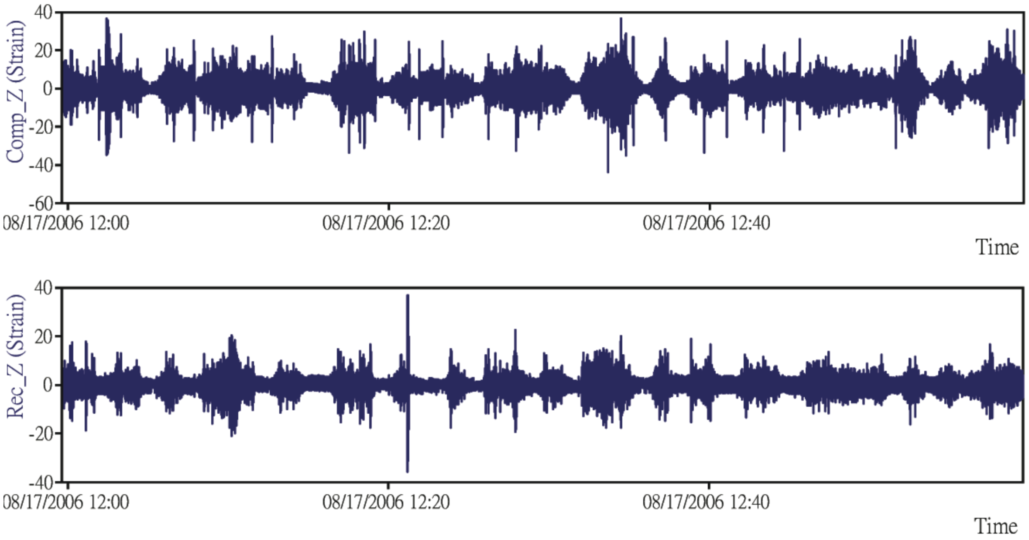


Figure 13: Typical results of the dynamic strain (vertical component) of the weld joints at the compressor (Comp) and rectifier (Rec) mounting brackets measured by FBG sensors. Stress levels and counts are converted to indexes according to BS7608 for structure life time projection.

FBG Sensors for Assessing Structural Integrity of Train Body Shell

Train body shells are subject to multi-dimensional forces, such as shearing and torsion stress. Distortion of train body shell can lead to window shatter, door jams and even door falling off which endanger the payload and passengers onboard. Early sign of body shell distortion exhibits as abnormal high stresses at door frames and window corners which eventually develops into cracks. The stress levels of a train body shell were measured in a trial test on a Hong Kong suburban line using a FBG sensor system which uses a broadband source, a tunable optical filter and a wavelength reference to determine the peak wavelength of the FBGs. Six FBG sensors were installed on a trailer car and another six FBG sensors were installed on the motor car of the same electrical multiple unit (EMU).

On the trailer car, three of the FBG sensors were attached to the corners of a window frame and 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. FBGs are attached to steel bar to measure the linear elongation and also the thermal expansion of the structures. A similar number of electrical strain gauges were located in close proximity to the FBG sensors for direct comparison.

(Fig. **14**) 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 s) to *Hung Hom* (time: 2500 s) station. The results from the two types of sensors, for most of the parts, agree with each other with maximum changes of strain occurring at about 2000 s (a changing station at which most of the passage alighted the train) and the strains were reduced when people alighted the train at the *Lo Wu* and *Hung Hum* terminus. Comprehensively, 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. This is because that the FBG system responds faster than the strain gauge (the response time of the FBG system is about 0.1 s while the strain system takes 1 s). The other difference is the high level of output signals from the strain gauges at around 1100 s. It is due to the fact that the train is electrically driven with a 25 kV AC overhead line and the power feeding system changes phase at that particular location which interferes the electrical strain gauges. However, it has no adverse effect to the FBG sensors, indicating superior performance of the FBG sensors because of their immunity to electromagnetic interference.

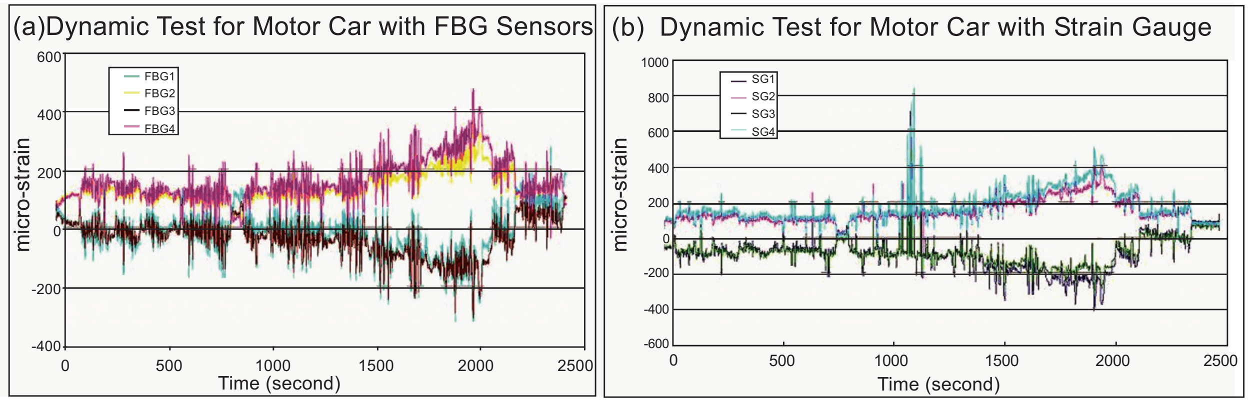


Figure 14: Results of dynamic load test. (a) FBG sensors; (b) Electrical strain gauges. Note that the FBG sensors are immune from the strong EMI picked up by the strain gauges around 1100 s.

Real-Time Condition Monitoring of Train Bogie Using FBG Sensors

Failure of critical moving components on a bogie can be very dangerous. For example, the hotbox problem is a classical issue which has led to numerous accidents. The term "hotbox" refers to the overheating of the axle box of a rail rolling stock which is resulting from a problematic axle bearing. If a hotbox is left unattended, the heat developed at the axle box will lead to axle fracturing and causing major derailment [43]. In the worst case, the hotbox can be an ignition source for inflammable goods [44], dust grains and even the rail track with combustible materials such as electrical cables and wood [45]. The traditional method to detect hotbox is by installing hotbox detectors or infrared cameras along the railway line at intermitted distance. The shortcoming of this method is that the hotbox detector or IR camera has no temperature record of the axle boxes and it is difficult to determine how bad the temperature of the each individual axle box is. Besides, it is also difficult to identify the problematic axle box even a hotbox alarm is being received, especially when the train is running on high speed because there is no proper means to identify the axle boxes. In addition to hotbox, malfunctioning brakes or brakes jam can also lead to serious incidents too, such as fire problem, train collision and derailment [46].

FBG sensors are also used to measure the temperature of critical components on a train, such as the moving parts on a bogie [47]. By making use of the temperature measurements, early problems of critical moving parts can be detected before their development into total failure. The principle of early problem detection for moving parts is based on the fact that a deteriorating moving part heats up abnormally due to excessive dragging friction and in the case when the moving part is jammed, tremendous amount of heat builds up. Failure of a critical moving part on a bogie can lead to suspension of train service, as well as damages to other components. For example, an unattended problematic motor bearing may cause substantial damages to the motor which is more costly to repair than fixing or early replacement. Conventionally, thermal sensitive stickers are used to measure the temperature of different mechanical and electrical parts of train bogies.

The thermal paper stickers, which have to be replaced frequently, give very crude readings and only record the maximum temperature experienced at the point of measurement. Thermocouples are sometimes employed when long-term temperature measurement is needed. However, thermocouples are susceptible to electromagnetic interference and the lead wires are limited to several meters, making them not suitable for measurement at locations that are far away from the drive cab. Complex cabling and connections also create additional problem when large number of sensing points are involved. In contrast, FBG sensors are fabricated onto tiny optical fibers which can be installed flexibly at points not reachable by electrical sensors. Hitherto, many of the sensing points may not be monitored in real time because of physical constraints due to the fitting of silencers around a traction motor, for example. With the use of FBG sensors, many of the previously inaccessible points now become readily accessible and the thermal profile of the instrumented bogie is accurately and easily obtained.

The work depicted in Ref. [47] is a test case in Hong Kong which involves the design and installation of a FBG temperature measurement system for 20 locations, including the hot spots near motor bearings and locations near brake pads, so as to investigate the practicality of using FBG sensors to detect early problems of critical moving parts of a train bogie. The system is also installed with a display console at the driving cab showing the temperature of all components and in the case when the temperature of a component exceeds the pre-set high alarm level, a warning signal will be displayed. (Fig. **15**) shows the locations of FBG sensors on the train bogie. (Fig. **16**) shows the actual FBG sensor installations on various bogie components. The test bogie is installed on the first car of a train that operates at the Airport Express Line (AEL) which links between the Hong Kong International Airport at Chek Lap Kok and the Central District of Hong Kong Island. It is one of the few dedicated airport railways in the world, covering a rail length of 35.3 km with two intermediate stations and an average traveling time of 24 minutes. The FBG sensors system has demonstrated its capability in identifying abnormal incidence on the bogie. On one occasion, it was observed by the FBG sensor system that the temperature around the braking pads became as high as 100°C throughout a normal service day, and this was exceptionally high as the normal temperature around the braking pads is around 40°C to 50°C. Upon further checking, it was found that the cause of such high temperature in the vicinity of the braking pads was a non-resettable power fault in power regeneration and hence the brakes had to stop the train mechanically from high speed without regenerative braking. (Fig. **17**) shows the temperature records of brake calipers for normal and abnormal brake operations. This information was not the intended objective of the trial but such example serves to illustrate that a wealth of information can be derived from the sensors if the data are interpreted properly.

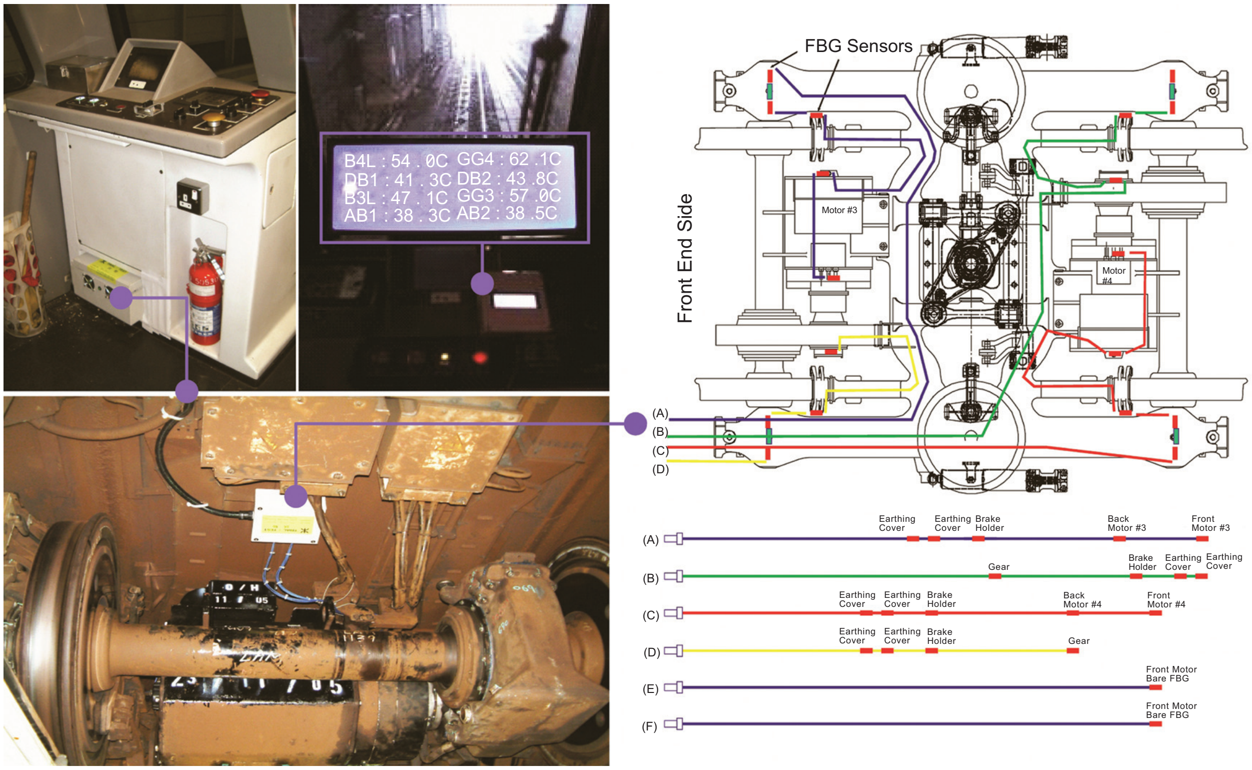
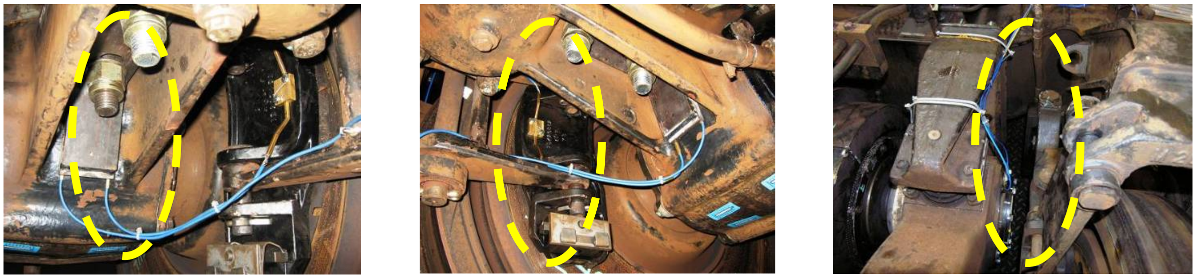


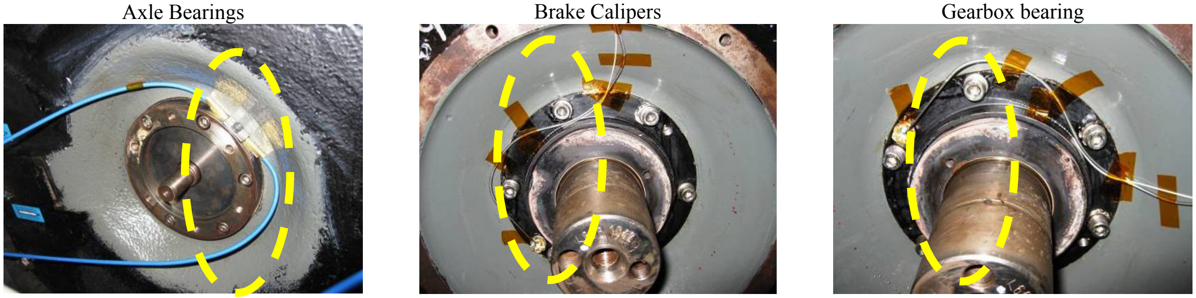
Figure 15: Locations and arrangement of FBG temperature sensors on train bogie. FBG sensors on train bogie are connected to the drive cab through a junction box beneath the car body with a multicore armored cable [46].

Condition Monitoring of Railway Catenary and Pantograph

Silica optical fiber is an excellent insulator of electricity and FBG sensors inscribed in silica optical fibers have found their role in high voltage applications, such as condition monitoring of high-voltage equipment [47], internal temperature measurement of power transformer [48] and icing temperature measurement of high voltage transmission line [49]. In railway systems, the catenary and pantograph bearing high voltages are the key components of the train electricity supply and their reliability are of great concern to railway operators. Conventionally, electrical strain gauges installed on pantograph were used to measure the contact force between the contact line and current collector [50] but there are several shortcomings. For example, the calibrated strain gauges and cables must be heavily insulated up to 25 kV which makes the system bulky and difficult to install. Besides, direct strain measurement at the current collector of the pantograph is not an effective means to measure contact force because the current collector is stiff and it exhibits low strain level.



Axle Bearings Brake Calipers Gearbox bearing



Motor Bearing (Rear) Motor Bearing (Front) Motor Bearing holder (Front)

Figure 16: FBG sensor packages and installation details on train bogie components.

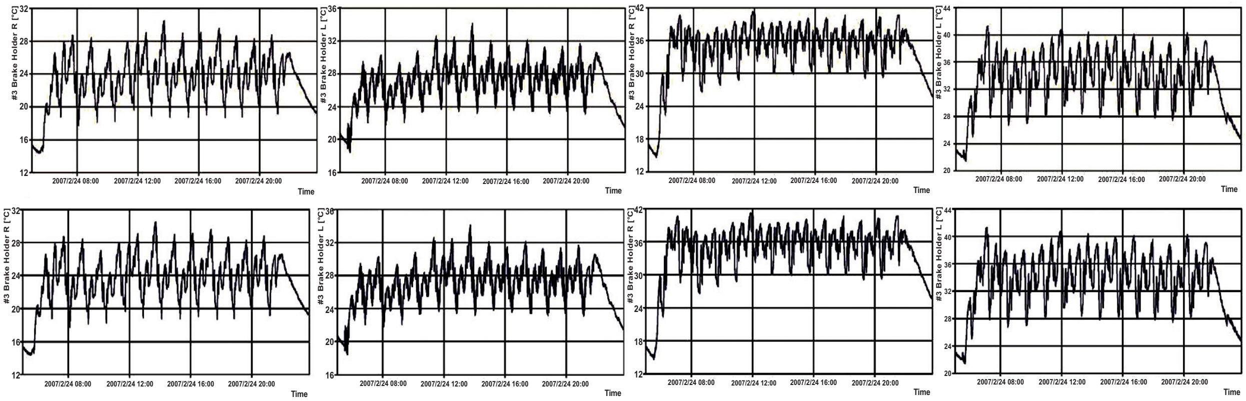
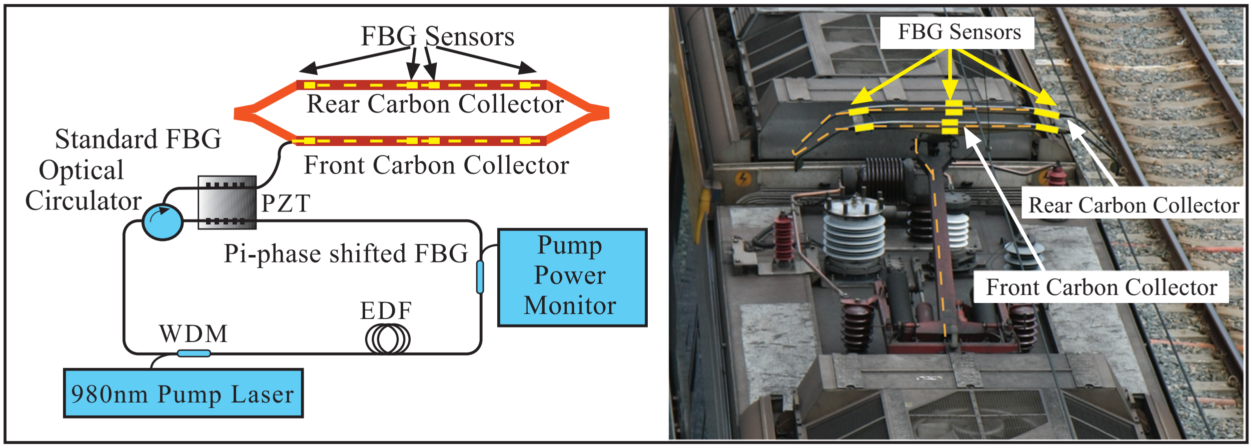


Figure 17: Temperatures of the four brake calipers on the test bogie during (a) normal operation with regenerative braking (average temperature 40°C-50°C), (b) abnormal operation without regenerative braking ((average temperature 80°C-100°C).

Alternatively, a system based on FBG sensors for measuring pantograph contact force with better features has been demonstrated [3]. (Fig. **18**) shows the setup of FBG sensors installed on pantograph current collectors for contact force measurement. Since FBG is small in size and multiple FBG sensors can be installed in series by a single optical fiber on the current collector. The overall size of the installation is still small as only minimal insulation and protection is required for the FBG sensors and optical fiber cable. The size and shape of the sensor installation affects the aerodynamic behavior of the pantograph and is crucial to its performance when the train is running at high speed. In terms of accuracy of contact force measurement, the multiple FBG sensor system adopts a three point bending approach which is more accurate than the indirect strain measurement method at the current collector using strain gauge. Moreover, FBG sensors sharing the same interrogation system can also measure the local temperatures on the current collector which is an additional feature not available in the conventional system. Catenary wire and contact line are important components of the railway power supply system and their integrity is critical to the availability of train services. Electrical overcurrent and hotspots at the catenary wire or contact wire can result in thermal overload which weakens the mechanical strength of the conductor. Eventually, prolonged thermal overloading will lead to conductor elongation and sagging and the life time of the contact wire and current collectors is reduced as a result. In order to measure the temperature of the catenary wire and contact wire, small size and light weight temperature sensors must be used to avoid interfering with the conductor. However, as heavy insulation is needed to protect electrical sensors from high voltage, conventional thermocouples are not suitable for the application. Instead of electrical sensors, it has been demonstrated that by using FBG sensors, the temperatures of the injections wires and supporting current wires were successfully measured [2]. (Fig. **19**) illustrates the setup for catenary temperature monitoring system using FBG sensors.



(a) (b)

Figure 18: (a) Fiber ring laser configuration for FBG interrogation, (b) FBG sensors installed on pantograph current collector for contact force measurement [3].

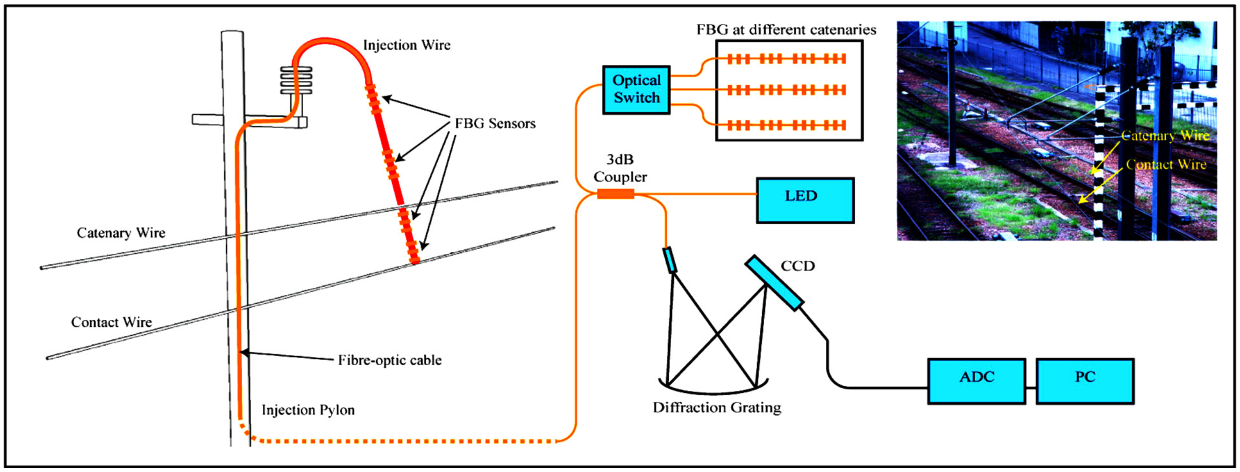


Figure 19: FBG based Catenary Temperature Monitoring System [2].

CONCLUSIONS

In this discussion, we outlined the advantages of using fiber Bragg grating sensor arrays for railway applications. The results obtained from field measurements over the past few years in collaboration with a railway operator are presented. The field measurement results together with the experiences gained from these projects demonstrated that distributed photonic sensor based on fiber Bragg gratings (FBGs) is an excellent candidate for the realization of smart condition monitoring systems for the railway industry. Two commercial systems, one installed on rail tracks (for the detection of wheel/rail interface response) and one installed on board of trains, have indeed been developed and are now being used by the local railway industry. The Hong Kong Polytechnic University is also striving to use our local experiences as the reference to promote the systems being developed to reputable railway operators/ consultants in other parts of the world.

Railways are nowadays the most effective means of mass transportation for both inter-city and intra-city traffic demands. Railway operations are unique in such a way that both infrastructure (or rights of ways) and vehicles are the exclusive assets to the operators and service providers alike. The safe and reliable operations and thus the service quality must be ensured by a comprehensive scheme of asset management. A reliable, accurate, remote-sensing, self-diagnostic and EMI-immuned condition monitoring system on the infrastructure and vehicles is deemed highly necessary and indeed strongly desired by the industry.

The FBG sensors inherently offer a practical solution for this railway condition monitoring application. They allows easy and flexible installation, remote sensing and low-distortion data collection over long distance, multiple parameter measurements, complete electromagnetic compatibility with electrified traction and signaling systems and proven interrogation system. The advantages and potentials of FBG sensing system starts to flourish in the early projects and the attained results so far are encouraging while the experiences are valuable for further development. The ultimate goal is to enhance the current setup to a general condition monitoring system conforming to the high requirements on safety and system integrity stipulated by the railway industry.

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