Exploration of Using FBG Sensor for Derailment Detector

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Abstract: - One of the most important safety assessments for running trains on rail is to evaluate the chance of derailment, particularly for train wheels riding in negotiating curve and track twist. The likelihood of derailment is very much depending on the conditions of track and the vehicle. The former refers to the deviation of the maintenance limits on the track geometries, while the latter refers to the conditions of the vehicle suspensions system together with their wheel profiles. Checking of both conditions will have to be done during off-traffic hours under pre-scheduled intervals, unless there are means for on-line in-service checking. This paper reports the use of optical sensors to detect the parameters for assessing the potential of derailment in railways.

Key-Words: - Fibre Bragg Grating, Nadal’s Limit, Derailment Risk Detection

1 Introduction
Railway engineers are understandably very conservative in the use of any new technology for train operations. Only proven technology with good track record will be used. Any change to the conventional equipment and methodology must be brought-in under a technically and commercially prudent manner. Fibre Bragg Grating (FBG) technology has been widely adopted in smart structure engineering with good records. Its application on railway engineering is limited at this stage, although there are applications such as the monitoring of the strain/stress on the train bogie frame composite structure [1]. An in depth review on the FBG characteristic reveals that it can bring massive benefits to railway operation by giving additional safety information in terms of derailment risk to the train operator who are charged with the duty to ensure safe operation of the train traffic at the main control center. Due to its unique construction nature, the cost of FBG derailment detector is relatively low when compared with the conventional technology, i.e. the strain gauge sensor. There is a good future in using FBG derailment detector to operate a smartly safe railway service.

Derailment caused by track twist is related to the combination of the horizontal guiding force and the reduction of the vertical wheel-load of the leading wheel. The Nadal’s limit \((Y/Q)\) on the lateral force \((Y)\) on the derailing wheel and its vertical load \((Q)\) is used to measure the probability of flange climbing. It has to be kept within an acceptable limit. If it exceeds the limit of 1.2, it means that the resultant of the two force vectors \(Y\) and \(Q\) may cause the guiding wheel to climb over the rail. As lateral forces are inevitably existing in train wheels riding on negotiating track curve and twist, it is important to ensure that the wheel sets do have adequate vertical loads to keep the \(Y/Q\) ratio to be within limits. Load transfer between wheel sets are thus critical and must be controlled also to fall within a reasonable limit, which is no more than 60\% load transfer from one wheel of an axle to the other. This paper explores a cost effective means for on-line derailment assessment of the unloading limit by Fibre Bragg Grating (FBG) technology. Field-test result indicates that FBG is technically viable to be mounted on critical track twist areas for real-time checking of the conditions of the interaction of the track and vehicle. These sensor can be used to assess promptly the potential risks of the vehicles from being off-loaded, i.e. derailment risk. FBG derailment detector has lots of advantages over their conventional
counterparts using strain gauge due to its electrical immunity to noise, multiplexing capability, compactness and more importantly, its relatively low cost of construction. Provided there is a weather proof and robust mounting methodology in the next phase, the FBG derailment detector will become a strong competitor to the conventional one. Once the physical integrity of FBG systems is proven to be satisfactory, one can extend its application to build a smartly safe railway.

2 Fibre Bragg Grating Technology

The feasibility of fabricating refractive index grating was discovered and reported by Hill et al. in 1978 [2]. Subsequently, Meltz et al. devised a method to control the fabrication of grating using UV laser [3]. Basically, when a germanium-doped silica core fibre is exposed to ultraviolet (UV) radiation (with wavelength around 240 nm), it results in a permanent change in the refractive index of the germanium-doped region, due to the photosensitivity nature of the fibre and, using such an exposure, it is possible to obtain refractive index changes by factors as large as $10^{-3}$ in germanium-doped silica fibre. If the fibre is exposed to a pair of interfering UV beams as shown below, then in regions of constructive interference which correspond to high UV intensity, the local refractive index will increase.

![Fig 1. UV beams on optical fibre through a phase mask](image)

At the same time, in regions of destructive interference, where the intensity of UV light is negligible, there is no index change. Therefore, an exposure to an interference pattern will result in a periodic refractive index modulation along the length of the fibre, the period of modulation being exactly equal to the spacing between the interference fringes.

3 Bragg Condition

When light is made to propagate through an UV exposed fibre with a periodically modulated refractive index, under certain conditions, the propagating light beam can be strongly coupled to a mode propagating in the backward direction. This happens when the Bragg condition is satisfied, i.e. the difference in the propagation constants of the two-coupled modes equals to the spatial frequency of the grating,

$$\beta_g - (-\beta_g) = K = \frac{2\pi}{\Lambda}$$

(1)

where, $\beta_g$ is the propagation constant of the forward propagating guided mode, $-\beta_g$ is that of the backward propagating guided mode, and $\Lambda$ is the spatial period of the grating.

![Fig 2. Vector diagram](image)

Figure 2 shows the corresponding vector diagram wherein the propagating vectors and the grating vector satisfy the condition given by (1). If $n_{eff}$ is the effective index of the mode, then equation (1) can be written as

$$2 \frac{2\pi}{\lambda_B} n_{eff} = - \frac{2\pi}{\Lambda}$$

(2)

or

$$\lambda_B = 2 \Lambda n_{eff}$$

(3)

where $\lambda_B$ is called the Bragg wavelength – that is, the wavelength that satisfies the Bragg condition. The Bragg wavelength is dependent on the effective index as well as the grating period.
4 Optical Interrogation System

The function of the optical interrogation system is to detect the wavelength shift in relation to the external perturbation. Due to the characteristics of FBG, the sensor possesses an intrinsic self-referencing capability as the sensed information is directly encoded in accordance to wavelength, which is an absolute parameter and independent of the light power and loss in the transmission fiber. This feature is widely acknowledged as one of the most important advantages of the FBG sensors.

The wavelength-encoded characteristic enables the quasi-distributed sensing of measurands, such as temperature, strain, and pressure etc., to be arbitrarily located at any point along the fiber.

Each FBG of a quasi-distributed FBG sensor array has a unique reflected wavelength. The wavelength interval between two neighboring FBGs should be greater than the maximum wavelength shift of the individual FBG as a result of external perturbations. In this way, the magnitude of the measure and at each arbitrary sensing position along the fiber can be tracked simultaneously. In other words, there could be many FBG sensors engraved on a single optical fibre. This is obviously a very significant advantage compared with conventional electrical sensors which require an independent circuit for each sensor.

It can be shown that when force is added to the sensor, the response of the reflective wavelength is different as shown below.

5 Off-loading Derailment Ratio

One of the most important safety assessments for running trains on rail is to assess the possibility of derailment, particularly in negotiating curve and track twist. The likelihood of derailment is very much depending on the conditioning of track and the vehicle. The former refers to the deviation of the maintenance limits on the track geometries, while the latter refers to the conditions of the vehicle suspensions system together with their wheel profiles. Checking of both conditions will have to be done during off-traffic hours under pre-scheduled intervals, unless there are means for on-line in-service checking. Derailment caused by track twist is related to the combination of the horizontal guiding force and the reduction of the vertical wheel-load of the leading wheel. The resultant of the two force vectors may cause
the guiding wheel to climb over the rail. The Nadal’s limit \((Y/Q)\) on the lateral force \((Y)\) on the derailing wheel and its vertical load \((Q)\) is used to measure the probability of flange climbing. It has to be kept within an acceptable limit. Fig 6 indicates the relationship of the forces at the wheel/rail interface.

As lateral force is inevitably present, hence for train wheels ridding on negotiating track curve and twist, it is important to ensure the wheels are set to have adequate vertical loads to keep the \(Y/Q\) ratio within limits. Load transfers between wheel sets are thus critical and must be controlled to be within a reasonable limit, which is generally agreed to be no more than 60% from one wheel of an axle to the other as shown in equation (4), where \(Q_1\) and \(Q_2\) are the vertical loads of two wheels of the same axle acting on rail.

- Off-loading Ratio \(\triangle Q/Q\)  
  \[
  = \frac{(Q_1 - Q_2)}{(Q_1 + Q_2)} < 0.6
  \]  

As the weight of the train exerts significant force upon the rail to generate a high strain/stress on the rail beam, the strain/stress will be a useful parameter in determining the off-loading ratio. Such observation is very interesting for engineers wanting to exploit the intrinsic advantages of FBG sensors in the design and development of derailment detector in railway engineering. Based on the Bragg’s Conditions described before, it can be understood easily that by measuring the changes in \(\lambda\), changes in \(\Lambda\) can be calculated by assuming that \(n_{\text{eff}}\) is relatively stable with respect to ambient changes. Since \(\Lambda\) is sensitive to both thermal expansion due to temperature changes and strain/stress, changes in \(\Lambda\) actually reflects strain/stress received and therefore the corresponding force/weight applied can be estimated by measuring changes in \(\lambda\) with suitable calibration.

Rail beam can actually be regarded as a simple structural beam experiencing compression, neutral and extension stratum as shown in the diagram below:

The weight of the train acting on the rail by the wheel would create both tensile strain and stress on the rail beam as shown in Fig 7. The corresponding changes in \(\Lambda\) thus resulted can be detected by attaching FBG sensors at positions 1 and 3 while on the neutral plane, the FBG could be used to measure the ambient temperature of the rail beam. Practically, changes in the FBG grating \(\Lambda\) sensed would be presented as changes in \(\lambda\) and hence, according to the principle, the weight of the train will trigger a shape change in wavelength \((\Delta \lambda)\). Once it is captured, it will represent the weight of the wheel acting on the rail \(Q\).

As the Off-loading Ratio \(\triangle Q/Q\) concerning only on the relativity ratio of the loadings and not on the absolute value of the vehicle weights, thus, the temperature effect and the need of fine-tuning and resolving the transfer function of the \(\Delta \lambda\) with respect to the weight \(Q\) do not matter as they all will be canceling out in deriving the off-loading ratio \(\triangle Q/Q\).

### 6 Site Test Arrangement

FBG sensors were fabricated and glued onto an intentionally twisted track beam as shown in Fig 8 and Fig 9, where there is a conventional off-loading measuring device installed using strain gauge technology. The weighing system is located at Lo Wu of the Kowloon-Canton Railway Corporation (KCRC) network, and is used to check the derailment ratio of the cross-border freight wagons loaded with goods from China to the KCRC track. If the wagon passes the checking point and it is found that the \(\triangle Q/Q\) is less than 0.6, it will be allowed to enter into the KCRC track. Otherwise, it will be either re-loaded to ensure a better load transfer between the axles or the train will be rejected.
back to China. The location and layout of the FBG sensors are shown in Fig 7 and Fig 8.

FBG sensors were placed near those strain gauge sensors. The range of lightwave’s wavelength of the FBG sensor is set within 1530nm – 1570nm in accordance to the specifications of the Optical Interrogation System being used in the test.

Optical fibre sensors were connected in series and were fed into the input port of the interrogator as displayed below in Fig 10. The block diagram of the complete set up for measurement is shown in Fig 11. Data obtained were then transferred to the computer for recording purpose. Results are presented in terms of continuous waveform, showing the weight of the train passing all the sensors.

7 Field Data Analysis

A freight wagon train rake composing one Co-Co diesel locomotive, i.e. with three axle bogies hauling five wagons with two axles per bogie were tested. All peaks of the strain
obtained as shown below in Fig 12 and Fig 13 for FBG Sensors at M1 Left and M2 Right respectively are supposed to indicate the force of the vehicle wheels acting on the rail through a transformation of strain from the rail which are supported on ballasts. It is obvious that distinguishable peak levels are observed. The first six are for the Co-Co locomotives, the remaining ones are for the five wagons. A large peak means the train is heavily loaded, while a small peak means that the trains are lighter. The absolute weighing result of the strain gauge is shown in Fig 14.

8 Weight Offset

The offset or the negative changes in wavelength so observed at each peak is mainly due to the compression seen by the sensor when the train wheels are approaching. The following bending moment diagram (Fig 15 and Fig 16) explains the situation.

9 Comparison of FBG Result with Strain Gauge Result

In checking the weight or the actual magnitude of the force Q of each wheel, one will refer to the change in wavelength ($\Delta \lambda$) from the peak to the trough before it, as it is the total reaction of the rail beam brought by the wheel load that counts (Fig 16). By checking all the $\Delta \lambda$ trough-peak of each wheel and then averaging them to identify the MEAN for normalizing the Q of each wheel in p.u. (per unit) basis, one can then compare the data obtained from the FBG sensors with that obtained by the conventional strain gauges. By using p.u. comparison, the inherent characteristics of the FBG and strain gauge systems will be canceling each other. The p.u. comparison of the FBG and the strain gauge results are shown in Fig 17.

The FBG results and the strain gauge results are in close approximation with errors of less than 10%, 15% and 20% at a confidence level of 50%, 70% and 85% respectively. The error incurred is believed to be the relatively primitive mounting of the FBGs on the rail. Thus, it is possible to use FBG sensors as a good alternative to the conventional strain gauge type derailment detector.

The conventional strain gauge would have electromagnetic issues when working under 25kV system which uses the rail to return the 25kV current back to the power transformer station. It is likely to pick up electrical noise which will affect the confidence level of the measurement results. As fiber optic sensor system is totally immune from electromagnetic interference (EMI) throughout the entire process, that is, from signal generation to signal transmission to the interrogation system. Hence there is no chance for any EMI disturbance in the system to degrade the integrity of the force Q detected with the proposed system. Indeed, as the problems associated with EMI is posing a great challenge to operators using conventional strain gauge systems, particularly for trains operating with a 25kV traction supply, there is a lot of incentives for the railway engineers to look into the possibility of using FBG sensors in the building of derailment sensing systems.
10 Total derailment risk detection using FBG

FBG axle counter is wavelength-encoded, and gives an absolute measurement of axle weight. This method avoids the problems with scale resetting and signal intensity variation that is plaguing the intensity, phase and polarization modulated sensing systems.

FBG axle counter have multiplexing ability. Coupled with a high spatial resolution of this kind of sensor, it makes the FBG system the best candidate in the building of a total derailment risk detector, i.e. the detection of \( \frac{Y}{Q} \) and \( \frac{\Delta Q}{Q} \) together at the same time at the same track twist and curve, for which the conventional strain gauge system would have difficulties in providing all these useful information. By multiplexing sensors onto the same optical fiber and distributing them round over the cross section of the rail as shown in Fig 18, the force \( Y \) and \( Q \) will be determined with suitable calibration.

11 Conclusion

Successful measurement results have now been obtained initially to support further development of FBG derailment detector in railway applications. The signals obtained by the FBG sensors are clear and accurate enough to warrant further development as compared with conventional strain gauge system. Taking into account also the potential capability of the FBG system in tailor-made systems in railway applications as listed below [4], a smart safe railway can be constructed using FBG. However further analysis and measurements together with a full blown development on rail are necessary before the FBG technology is matured into practical usage in a highly conservative industry.

a. Counting the numbers of axles in and out of a given section (track circuit occupation)
b. Train identification by tracking the differences of axle bases, weights and car numbers of various train stocks.
c. Speed detection

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Reference

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