A Trackside Sensor System for Train Axle Counting by Fiber Bragg Grating Accelerometer

Kivilcim Yüksel[(a)], Damien Kinet[(b)], Veronique Moeyaert[(b)], Georges Kouroussis[(b)], and Christophe Caucheteur[(b)]

[(a)] Izmir Institute of Technology, Electronics Engineering Department, 35430 Urla, İzmir, Turkey
[(b)] University of Mons, Boulevard Dolez 31, 7000 Mons, Belgium
Author e-mail address: kivilcimyuksel@iyte.edu.tr

Abstract: An efficient method for railway traffic monitoring is presented. It uses FBG-based accelerometer together with an optimized signal processing. Sensors can be easily installed on a sleeper, without requiring interruption of the railway operability.

OCIS codes: (060.3735) Fiber Bragg gratings; (060.2370) Fiber optic sensors; (280.0280) Remote sensing and sensors; (120.3930) Metrological instrumentation

1. Introduction

High safety integrity level, longer service availability, and optimal operation are the major concerns in today's railway transport systems. Smart monitoring systems should address these issues without interrupting railway operability. Many successful works have been carried out to provide railway monitoring functions (i.e. train identification, axle counting, defect determination, flat wheel detection, weigh-in-motion, speed and acceleration estimation) using Fiber Bragg Grating (FBG) sensors installed on track [1-6]. Most of them are based on strain measurement due to the train passage, where the FBG sensors were manually placed on particular locations (or orientations) and bonded to the foot of the rail beam. This type of sensor implementation requires a careful surface cleaning (e.g. rust removing and polishing), together with the use of dedicated glues (e.g. cyanoacrylate, UV-photo-polymerized urethane-acrylate) and good mechanical protection (e.g. reinforced tubes, armored cables). These steps also imply service disruption during the sensor installation (i.e. direct and secure access to the rails). Therefore, there remains ample room for concurrent minimally-invasive railway monitoring approaches as no commercial product based on optical fiber sensors is currently deployed for safety monitoring, in real systems [7].

This paper presents a highly sensitive and electromagnetic interference-free means for axle counting and train speed determination based on vibration measurement. FBG accelerometers placed on sleeper have been employed as sensor heads, which significantly facilitated the field sensor installation work compared to the positioning on the foot of the rail. An optimized signal demodulation algorithm has been effectively used for the detection of train wheel passage. Excellent capability of the developed system for axle counting and train speed determination has been demonstrated through field trials that were carried out on a Belgian railway line, during its normal operation.

Easy installation, multi-function diagnosis, good data integrity, and compatibility with fiber optic sensors make the proposed sensor a good candidate to provide railway signaling systems with better safety assurance.

2. Field Measurements

The monitoring set up used in the field measurements was positioned along a track where train speed is limited to 100 km h^{-1}. In general, the train speed at the measurement point is about 30-90 km h^{-1}.

The layout of the whole monitoring system used in our measurements is shown in Fig. 1-a. It comprises one FBG accelerometer mounted on a sleeper, various FBG strain sensors placed on the rails, couplers, junction boxes, and the protected feeder cable providing the connection between the sensor network and the interrogator. A commercial accelerometer (*OS7100, MicronOptics*) with one axis configuration was attached on the sleeper and connected to the sensors network, as shown in Fig. 1-b. The frequency range of this particular accelerometer, from DC up to a few hundred Hertz, was sufficient for both axle counting and speed calculations.

For a given measurement, the outputs of the FBG strain sensors and the FBG accelerometer are acquired simultaneously on input channels of the interrogator that is located in a remote equipment room. Commercial spectrometer-based interrogators with acquisition rates between 1 kHz to 3 kHz, an absolute wavelength measurement accuracy of 40 pm and a precision of 1 pm were used in the measurements.

Railway monitoring system was tested over a time span of about 6 months, which both allowed relevant statistics on the efficiency and proved the robustness of the overall system. Real-time videos have also been taken from a monitoring camera facility for train identification purpose and reference speed calculation.

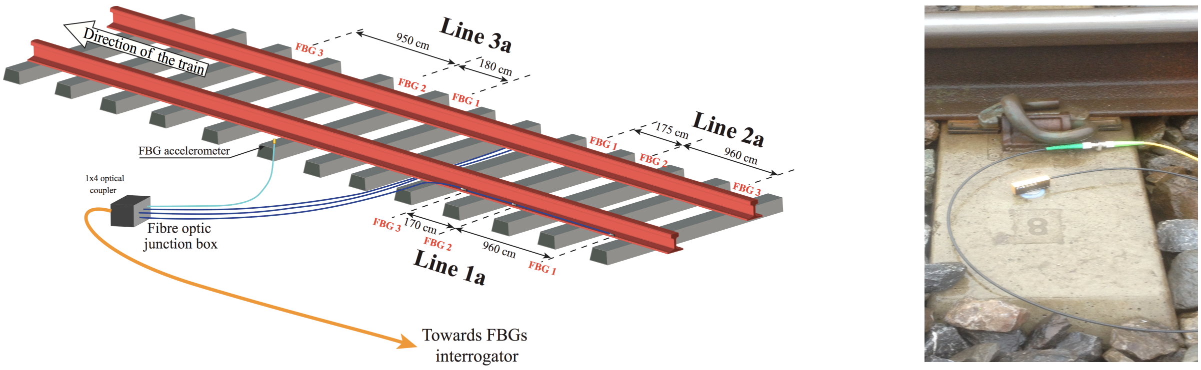

***Fig. 1**. (a) Schematic of the sensors installed on the rail track, (b) photograph of the accelerometer placed on a sleeper.*

FBG accelerometer includes a flexible cantilever with an FBG mounted on it at one end, and a mass at the other end. When a vertical acceleration is applied on the cantilever beam, a varying axial strain is created on the grating (due to the alternation of flexion and compression), which is proportional to the distance from the neutral axis. The induced strain is demodulated by measuring the corresponding Bragg wavelength shift (alternating between positive and negative extremes).

The typical traces measured on the test rail track by using the FBG strain sensor and the accelerometer are compared in Fig. 2. They both correspond to the passage of a 6-car passenger train. The axle positions are clearly visible in the upper trace (FBG strain sensor); whereas some further signal processing is required in the lower case (FBG accelerometer on the sleeper). The noisy nature of the accelerometer output is attributed to the effect of various high frequency components due to the effects of track flexibility and wheel/rail sliding on the vibration signature of the vehicle [8] together with the unwanted residual vibrations of the accelerometer before and after the passage of the wheels. The effect of these vibrations has to be filtered out in our trace analysis, as explained in the following paragraph.

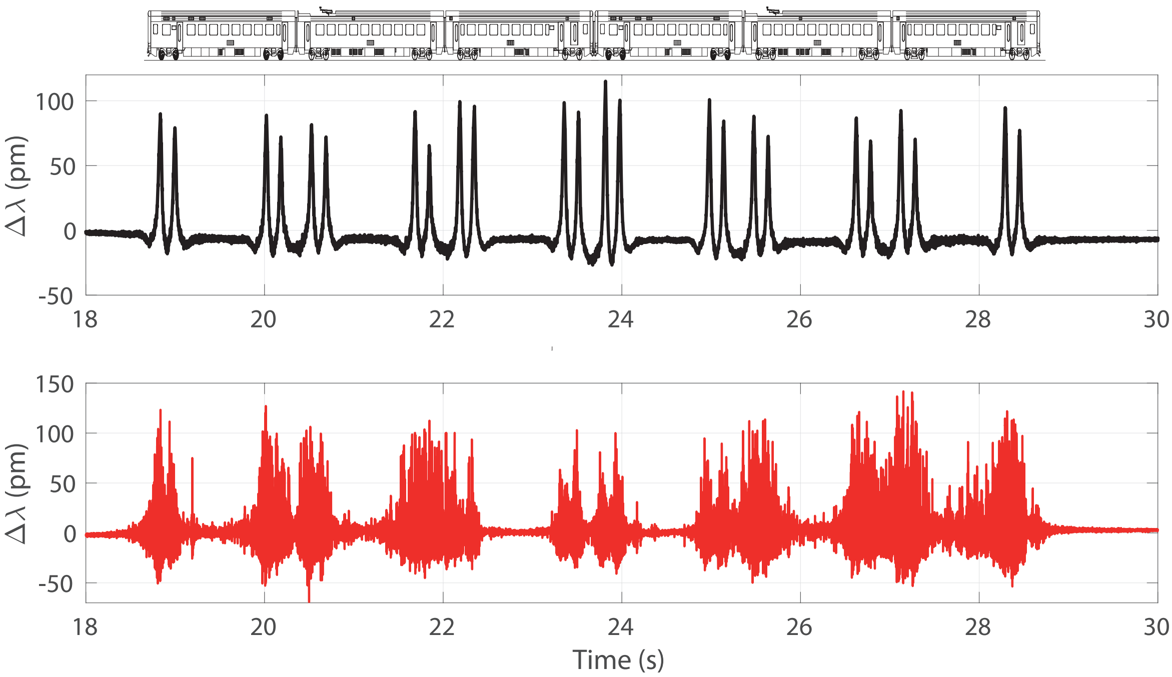

***Fig. 2.** Trace of a 6-car train circulating at 60 km h^{-1} measured using (a) FBG strain sensor on the foot (b) FBG accelerometer on the sleeper.*

3. Trace Analysis and Results

The relationship between the main geometry of the train (i.e. wheel set spacing, bogie spacing and carriage length) and the spectral content of rail vibration has already been demonstrated and successfully validated in a previous work [8]. When the vehicle speed is assumed to be constant, the periodicity of the axle (L_a), the bogie (L_b), and the cars (L_c) lead to three different amplitude modulations of the spectrum having corresponding frequency components, f_a, f_b, and f_c [8]. In addition to these dominant frequency components, vertical vibrations between the rail and the sleepers, together with the vehicle dynamics affect the vertical track dynamics [9].

Moreover, there are residual vibrations recorded by the accelerometer when the wheels are approaching to (and leaving from) the sensor location.

These unwanted frequency components have been eliminated by using low-pass filters (LPF) in the proposed trace analysis. Instead of applying a single LPF on the whole trace however, we first divided the raw signal at the accelerometer output into segments. Indeed, the vibration signatures (hence the frequency response) corresponding to different parts of the train differ from each other, depending on the train geometry (i.e. the total length, number of cars, and the wheel set positions), the train load and the wheel set conditions. Once the raw trace is low-pass filtered, an envelope detection algorithm is applied on the signal to determine the axle positions (peaks of the envelope trace).

In the final stage of the signal processing algorithm, the analyzed segments are merged to re-obtain the global processed signal. Axle positions now being indicated on this signal, the time difference between the last axle and the first axle positions is determined. Knowing the total length of the train, the average speed is then calculated. The flowchart of the signal processing steps applied on the raw trace is summarized in Fig. 3.

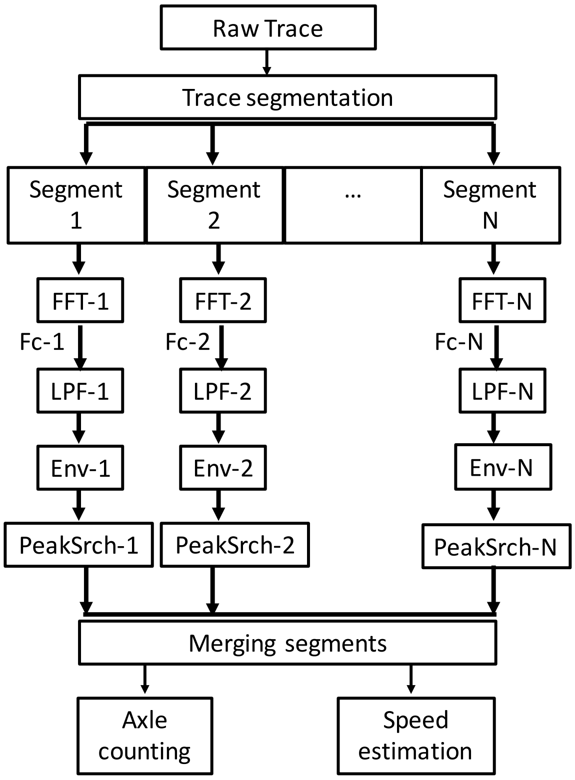

Fig. 3. *Flowchart of the data processing steps. (FFT: Fast Fourier Transform, F_{c-i}: cut-off frequency for the i^{th} segment, LPF: Low Pass Filter, Env: Envelope detection). The frequency response of each segment is individually analyzed (FFT on each segment) to obtain the value of the cut-off frequency to be applied on the filter. Instead of applying one global cut-off frequency, individual cut-off frequencies adapted to the frequency responses of these different parts of the train provide a more effective way to clean vibration noise from the raw signal.*

Figure 4 represents two traces before and after the proposed data processing steps for two example cases; a 3-car Desiro AM08 train at 84 km h^{-1}, and 6-car AM96 train at 64 km h^{-1}. As can be seen in the figure, the axle positions in the raw traces are blurred with the vibration noise components but are clearly resolved after the suppression of this effect with the proposed signal processing steps explained above (cf. Fig. 3).

Thanks to our long-term outdoor installation, numerous field tests were carried out (with intervals of few months) to validate both the hardware of the monitoring system and the related signal demodulation algorithm. Results demonstrate the capability of the proposed system in both counting the number of axles of a given track section (without any miscount), as well as the average train speed estimation.

Table 1 summarizes some examples of axle counting and speed measurement results for different train types. Speed values obtained by the proposed system are compared with that coming from FBG strain sensors deployed on the field trial as well as reference videos. The error on the reference speed values is determined by the camera resolution (which is 1/30 s). Based on the resolution value and time intervals measured for all the trains, the maximum absolute error was calculated as 1 km h^{-1}.

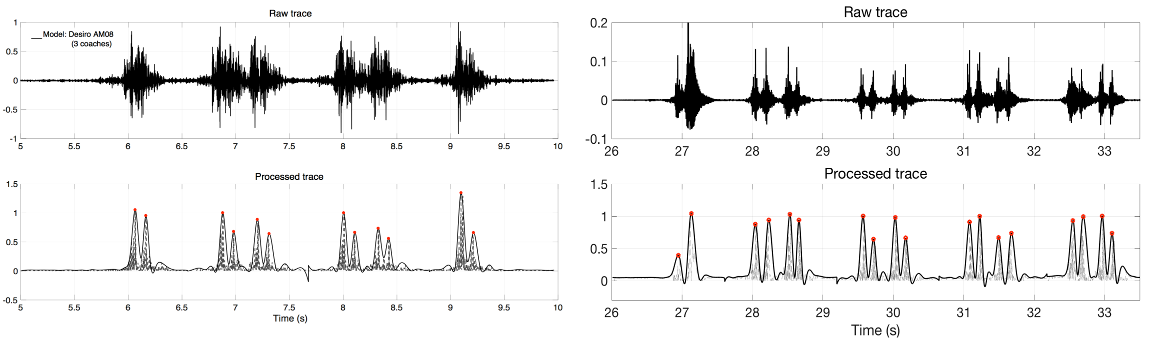

Fig. 4. *Measured accelerometer responses as a function of time before (raw trace) and after (processed trace) the data processing steps (red circles represent the axle points) due to the passage of a train a) 3-car Desiro AM08 with 12 wheels circulating at 84 km h^{-1} (b) 6-car AM96 with 24 wheels circulating at 64 km h^{-1} (only first 18 wheels are shown for the sake of figure space)*

Train number	Measurement Date	Train type	Number of cars	Number of axles	Reference Speed, based on Video (km h^{-1})	Speed Based on FBG sensor, (km h^{-1})	Speed Based on accelerometer (km h^{-1})
1	21.11.2016	AM-73	2	8	52.02	51.66	51.33
2	01.03.2017	CityRail70	2	8	57.60	58.19	57.04
3	31.03.2017	Desiro AM-08	3	12	47.93	48.80	49.50
4	01.03.2017	AM-96	6	24	65.10	63.02	64.33
5	01.03.2017	M6	7	30	49.48	48.51	50.10

Table 1. Comparison of measured average speed by three methods for five example cases

4. Conclusions

In this paper, the feasibility of using fiber Bragg grating accelerometers placed on sleepers for railway traffic monitoring has been well proven as a very competitive alternative to the use of strain sensors. The measurement results obtained from field trials demonstrate the excellent capability of the proposed system to achieve the axle counting functionality, together with a very good estimate of train speed ($\pm$1 km h^{-1}). The proposed system is a very useful alternative to the existing train axle counting approaches as its installation can be easily made on a sleeper, without requiring interruption of the railway operability.

[1] G. Kouroussis, C. Caucheteur D. Kinet, G. Alexandrou, O. Verlinden, and V. Moeyaert, "Review of trackside monitoring solutions: from strain gages to optical fibre sensors," Sensors. **15,** 20115–39 (2015).

[2] C L. Wei, C.C. Lai, S.Y. Liu, W.H. Chung, T.K. Ho, H.Y. Tam, S.L. Ho, A. McCusker, J. Kam and K.Y. Lee, "A fiber Bragg grating sensor system for train axle counting," *IEEE Sensors J.,* **10**, 1905-1911, (2010).

[3] A. Iele, V. Lopez, A. Laudati, N. Mazzino, G. Bocchetti, A. Cutolo, A. Cusano, "Fiber Optic Sensing System for Weighing in Motion (WIM) and Wheel Flat Detection(WFD) in Railways Assets: The TWBCS System," in 8th European Workshop on Structural Health Monitoring, (EWSHM, 2016), pp. 01-10.

[4] F. Mennella, A. Laudati, M. Esposito, A. Cusano, A. Cutolo, M. Giordano, S. Campopiano and G. Bregliot, "Railway monitoring and train tracking by fiber Bragg grating sensors," in SPIE 6619, (2007), pp. 66193H.

[5] M. L. Filograno, P. Corredera Guillen, A. Rodriguez-Barrios, S. Martin-Lopez, M. Rodriguez-Plaza, A. Andres-Algacil, and M. Gonzalez-Herraez "Real-time monitoring of railway traffic using fiber Bragg grating sensors," *IEEE Sensors J.,* **12**, 85-92, (2012).

[6] S.J. Buggy, S. W. James, S. Staines, R Carroll, P Kitson, D Farrington, L Drewett, J Jaiswal and R P Tatam "Railway track component condition monitoring using optical fibre Bragg grating sensors," *Meas. Sci. Technol.,* **27**, 055201, (2016).

[7] A. Alemi, F. Corman, G. Lodewjks, "Condition monitoring approaches for the detection of railway wheel defects," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 231, 961-981, (2017).

[8] G. Kouroussis, D. Kinet, E. Mendoza, J. Dupuy, V. Moeyaert and C. Caucheteur, "Edge-filter technique and dominant frequency analysis for high-speed railway monitoring with fiber Bragg gratings," Smart Mater. Struct. **25,** 075029 (2016).

[9] G. Kouroussis, D.P. Connolly and O. Verlinden, "Railway-induced ground vibrations – a review of vehicle effects," International Journal of Rail Transportation. **2,** 69-110 (2016).