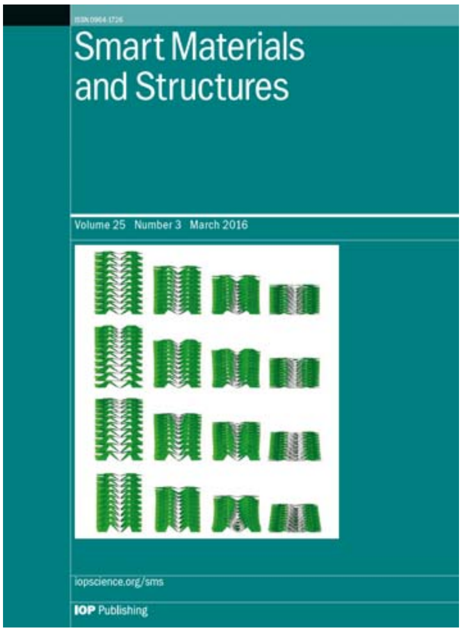

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Edge-filter technique and dominant frequency analysis for high-speed railway monitoring with fiber Bragg gratings

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Abstract

Structural health and operation monitoring are of growing interest in the development of railway networks. Conventional systems of infrastructure monitoring already exist (e.g. axle counters, track circuits) but present some drawbacks. Alternative solutions are therefore studied and developed. In this field, optical fiber sensors, and more particularly fiber Bragg grating (FBG) sensors, are particularly relevant due to their immunity to electromagnetic fields and simple wavelength-division-multiplexing capability. Field trials conducted up to now have demonstrated that FBG sensors provide useful information about train composition, positioning, speed, acceleration and weigh-in-motion estimations. Nevertheless, for practical deployment, cost-effectiveness should be ensured, specifically at the interrogator side that has also to be fast ($>$1 kHz repetition rate), accurate ($\sim$1 pm wavelength shift) and reliable. To reach this objective, we propose in this paper to associate a low cost and high-speed interrogator coupled with an adequate signal-processing algorithm to dynamically monitor cascaded wavelength-multiplexed FBGs and to accurately capture the parameters of interest for railway traffic monitoring. This method has been field-tested with a Redondo Optics Inc. interrogator based on the well-known edge-filter demodulation technique. To determine the train speed from the raw data, a dominant frequency analysis has been implemented. Using this original method, we show that we can retrieve the speed of the trains, even when the time history strain signature is strongly affected by the measurement noise. The results are assessed by complimentary data obtained from a spectrometer-based FBG interrogator.

Keywords: optical fiber sensor, railway monitoring, fiber Bragg grating, edge filter technique

(Some figures may appear in colour only in the online journal)

1. Introduction

Passengers and freight railway traffics are continuously growing, as they allow fast connections while mitigating CO_2 emission resulting from combustion engines. To ensure safety, metrology devices (e.g. track circuits and axle counters) are regularly placed along the rail tracks. A track circuit is a simple electrical device used to detect the presence of a train on rail tracks. It can also detect a rail track breakage. Axle counters detect the passing of a train between two points on a track. In this case, a counting head is installed at both ends of a rail section. This pair of counting heads acts as a counter increment and decrement, respectively. If the net count after the passage of a train is evaluated as zero, the section is presumed to be free for another train.

As continuous efforts are made towards the overall improvement of railway safety, investigations are carried out to find an alternative solution to these existing techniques. New techniques are also envisaged to bring additional features such as speed and acceleration measurements, as well as weigh-in-motion determination. Due to their inherent and unique advantages (electromagnetic immunity, small size, low attenuation, possibility to multiplex a high number of sensing points, …), optical fibers and more particularly fiber Bragg gratings (FBG) sensors are studied and developed for this application [1, 2].

FBGs are usually photo-imprinted in the core of telecommunication-grade optical fibers by means of a UV laser technique [3]. They act as bandpass filters, reflecting some wavelengths around the so-called Bragg wavelength $\lambda_B = 2n_{\mathrm{eff}}\Lambda$ where n_{eff} is the effective refractive of the fiber core at the Bragg wavelength and Λ is the grating period. As they are characterized by a narrow-band amplitude spectrum, they can be easily wavelength-multiplexed in a single optical fiber, yielding quasi-distributed sensing for which a single interrogation unit (covering a band of $\sim$100 nm for instance) can be shared by several tens of sensing heads. FBGs are intrinsically sensitive to temperature changes and axial strain effects, which both induce a linear and reversible shift of the Bragg wavelength in the amplitude spectrum. Besides railway applications, FBG sensors find many applications in structural health monitoring [4, 5], civil engineering [6], oil & gas industries [7], …

Another important consideration in FBG sensing is the interrogator. An interrogator is a device that injects light into an optical fiber containing Bragg gratings while reading the reflected or transmitted amplitude spectrum. In practice, when an FBG is subject to an axial strain or a temperature change, a linear shift of its Bragg wavelength occurs, as both n_{eff} and Λ are sensitive to these external parameters. The sensitivities are of the order of $10\,\mathrm{pm}\,^{\circ}\mathrm{C}^{-1}$ and $1\,\mathrm{pm}/\mu\varepsilon$ at 1550 nm (wavelength of minimum attenuation of standard single-mode optical fibers). Therefore, the objective of any interrogator is the precise determination of the Bragg wavelength shift, which often results from a trade-off between accuracy, time and cost issues. Currently, the most accurate FBG commercially-available interrogators rely on a tunable laser source and a detector. They provide an absolute accuracy of 1 pm in the determination of the Bragg wavelength but are usually limited to an acquisition rate below 10 Hz, which is not suitable for dynamic measurements such as railway monitoring. It turns out that rapid measurements are obtained with broadband optical sources coupled with an interrogation technique based either on a wavelength–space conversion (spectrometer technique containing a diffraction grating and a charge-coupled device array [8]) or on a wavelength–amplitude conversion (edge filter technique [9]). The latter is by far the less expensive and easiest solution but it can also rapidly suffer from poor resolution when the optical budget is limited or when the gratings present a wavelength bias with respect to the edge of the filter.

Up to now, field trials conducted with FBGs sensors glued on the foot of the rail have demonstrated that they provide relevant information about train composition, positioning, speed, acceleration and weigh-in-motion estimations [10–13]. Generally, the best sensor location is between a sleeper bay, where a maximum of information can be obtained, as pointed out in [2]. When the wheel of a train passes over that position, the sensor undergoes a maximum Bragg wavelength shift. A high acquisition rate is required to record this shift with a good resolution. For instance, for a train circulating at $120\,\mathrm{km\,h}^{-1}$, two consecutive axles distant by 2 m can be detected if the acquisition rate is superior to 20 Hz. For well-resolved measurements, a high sampling rate is required so that the acquisition rate should be higher than 100 Hz. Hence, recording at a sufficient speed the Bragg wavelength evolution as a function of time allows obtaining a complete train identification. Using a couple of FBGs, it was also shown that wheel flats could be detected by this sensing solution [14]. Nevertheless, for practical deployment along railtracks, the cost-effectiveness of this technology should be ensured, specifically at the interrogator side.

To reach this relevant objective, we use a low cost and high-speed interrogator based on wavelength/amplitude conversion, as already done in [11]. The originality of our work arises from the application of an adequate signal-processing algorithm to dynamically monitor the FBGs and accurately capture the parameters of interest for modern railway traffic monitoring. Our method has been field-tested with a Redondo Optics Inc. interrogator based on the edge-filter demodulation technique. It uses an array waveguide grating architecture to separate FBG sensor wavelengths and a wavelength-division-multiplexing filter to convert the Bragg wavelength shifts (due to the strain applied by the train) into a linear intensity variation. To process the raw data (that can be noisy depending on the available optical power budget or the strain transfer to the grating), a dominant frequencies method has been implemented. We show that we can retrieve a very good estimate of the train speed, even when the time domain strain signature is strongly affected by the interrogator's noise. The results are compared to the data obtained from a commercially available dynamic FBG interrogator based on a spectrometer and to video recordings. They all match, attesting the efficiency of the proposed method.

In the following, we will first describe the field tests that were conducted and the original demodulation technique that was successfully implemented. Then, we will present the obtained results.

2. Experiments

2.1. Manufacturing of the sensors

5 mm long uniform FBGs were photo-imprinted in the core of hydrogen-loaded telecommunication-grade single-mode

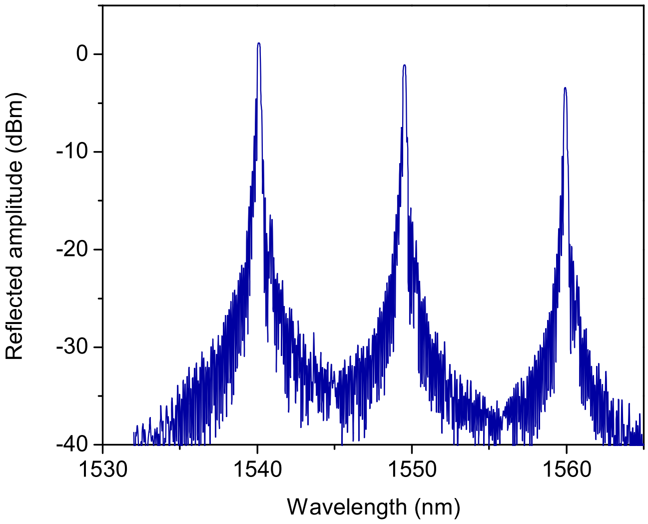


Figure 1. Reflected amplitude spectrum of three uniform FBGs wavelength-multiplexed in a single optical fiber.

optical fibers, using the frequency-doubled Argon laser technique described in [15]. A Lloyd mirror configuration was used to produce gratings at different Bragg wavelengths in a single optical fiber. After the writing process, the gratings were annealed at 80 °C during 24 h to stabilize their physical properties. FBGs were photo-inscribed at wavelengths of 1540 nm, 1550 nm and 1560 nm, respectively, to match the center of the filters contained in the interrogator (see section 2.3.). Figure 1 depicts the reflected amplitude spectrum of the three gratings cascaded in a single optical fiber. The latter was measured with a broadband optical source, an optical spectrum analyzer and a circulator.

2.2. Positioning of the sensors on a railtrack

The fibers containing the FBGs were positioned on the Mons-Liège rail tracks (Belgium), nearby the railway station of La Louvière Sud. Optical fibers were glued on the foot of the rail at the FBG location using a UV-photopolymerized urethane-acrylate glue. Prior to the gluing process that lasts 1 min, the rail was polished using a grinder. For an optimal strain transduction, bare gratings are glued, so that the optical fiber thickness at that location is only 125 μm. Then, to ensure a good mechanical protection, at each side of the grating, the fiber was inserted into an inner loose tube of 900 μm (red part in the picture), itself placed inside an outer Kevlar reinforced tube of 3 mm. This cable goes to a waterproof connection box buried in a gutter, to which the interrogator can be connected.

Figure 2(a) displays a picture of the optical fibers glued on the foot of the rail for measuring axial strain while figure 2(b) presents a schematic representation of the FBG locations and connections to the interrogator. It can be seen that in the field configuration the chosen distances between consecutive FBGs are 1.7 m and 9.6 m, respectively. In both cases, the gratings were positioned exactly between two sleepers, according to the recommendation in [2].

2.3. Interrogation of the sensors

The fiber containing the Bragg gratings was connected to the miniaturized interrogator FBGT-300 from Redondo Optics. Its sampling frequency is 10 kHz, which is comfortable for railway monitoring applications. As aforementioned, this unit contains three different filters, so that three FBGs can be simultaneously interrogated. Using another instrument can increase this number: for instance, the FBGT-1200 interrogator can demodulate up to 12 sensors simultaneously but at the expenses of device cost.

Basically, the edge filtering technique provides an output voltage that is linearly proportional to the Bragg wavelength shift and hence to the applied force. Its measurement principle is depicted in figure 3. A wideband optical source (bandwidth ~50 nm) launches light into the fiber containing the FBGs through an optical circulator. The reflected light is then split (demultiplexed) into different wavelength bands, using an arrayed-waveguide grating. Each subsequent wavelength band is then sent into its corresponding passive optical edge filter. The latter presents a linear amplitude evolution in a wavelength range of several nanometers (almost 8 nm in our case), which is at least ten-fold higher than the width of the FBG main reflection band (~0.1–1.0 nm, depending on the grating physical length). This is illustrated in figure 4 where the typical spectrum of an edge filter is presented and compared the FBG reflected spectrum. In both cases, the amplitudes are normalized. Hence, the filter encodes the wavelength position of the reflected signal into a mean amplitude level. At the output of each filter, a photodiode measures this light intensity and provides a voltage proportional to the Bragg wavelength shift. The bandwidth of each filter is such that it can measure a wavelength shift of the Bragg resonance as large as ~±2 nm, which corresponds to an axial strain of ±2000 $\mu\varepsilon$. This is by far enough to address FBGs strain gages used for railway monitoring.

Figure 5(a) shows the typical signature of a train composed by two locomotives and five coaches and circulating at the speed of ~50 km h^{-1}. It can be seen that two closely spaced wheels exhibit a typical temporal signature with patterns showing an alternation between positive, negative and again positive voltage evolutions. This translates the dynamic stress (changing between traction and compression) undergone by the grating when a pair of wheels is crossing the FBG location. The number of positive peaks exactly corresponds to the number of axles, confirming that the acquisition rate is high enough so that these raw data can be used to determine the speed of the train, provided that its coach's composition is known.

The main advantages of this technique are undoubtedly its high acquisition rate combined to its cost-effectiveness, as relatively low cost components can be used. However, its efficiency is strongly affected by power fluctuations at the interrogator input that may occur due for instance to unwanted power decrease of the source or loss in the optical fiber links. The same effect is also obtained when the Bragg gratings are no longer matched with the center of the edge

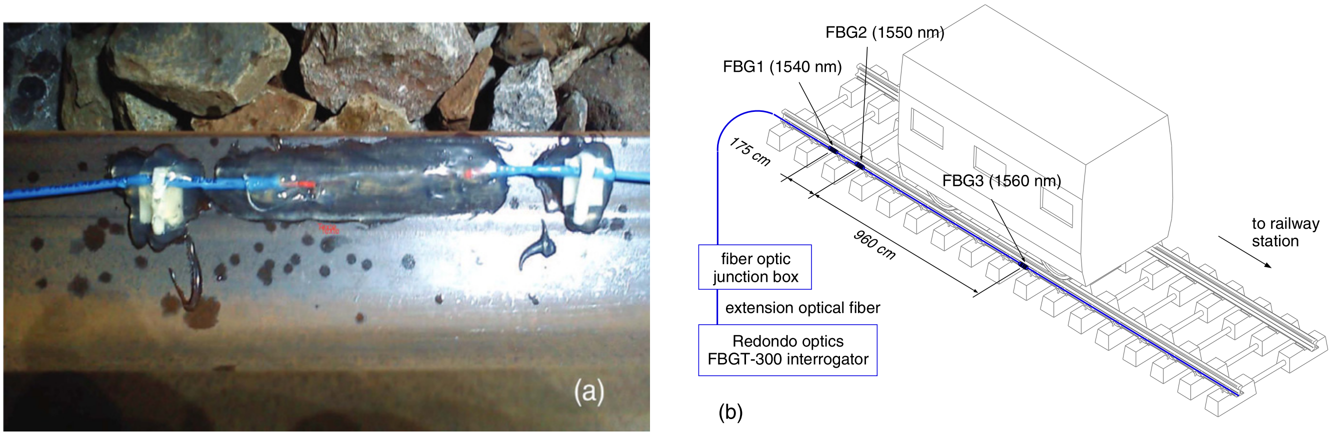


Figure 2. (a) FBG sensors glued on the foot of the rail and (b) schematic of the FBG sensors installed on the Mons-Liège track.

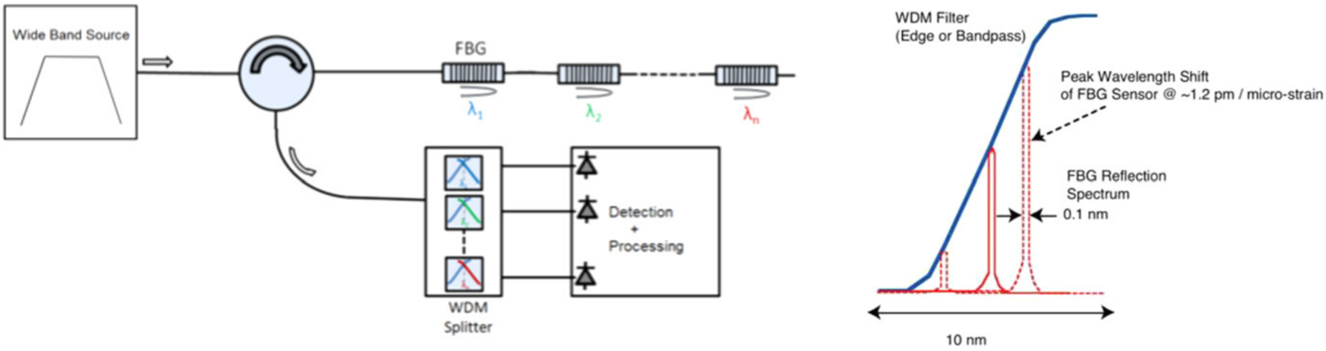


Figure 3. Operating principle of the edge filtering technique.

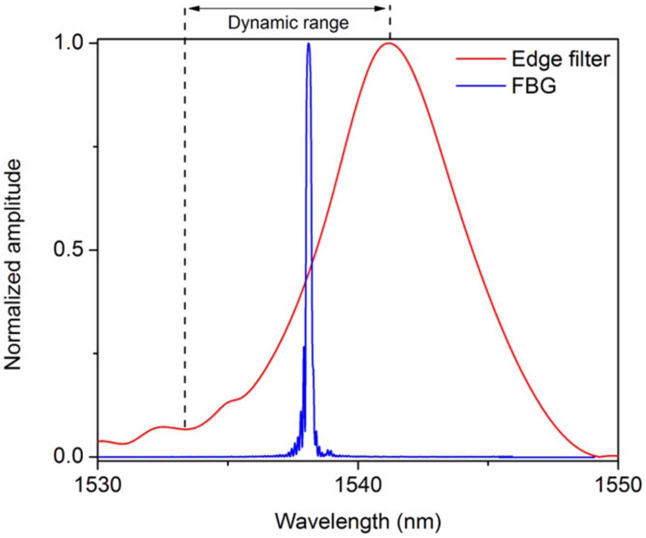


Figure 4. Spectrum of the edge filter and reflected amplitude spectrum of an FBG used in this work.

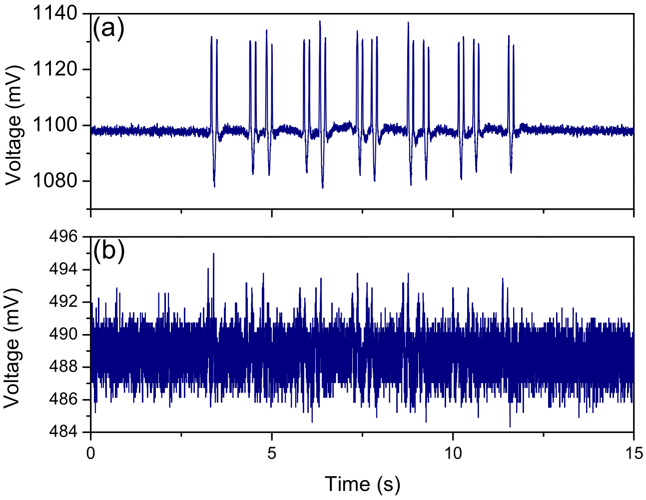
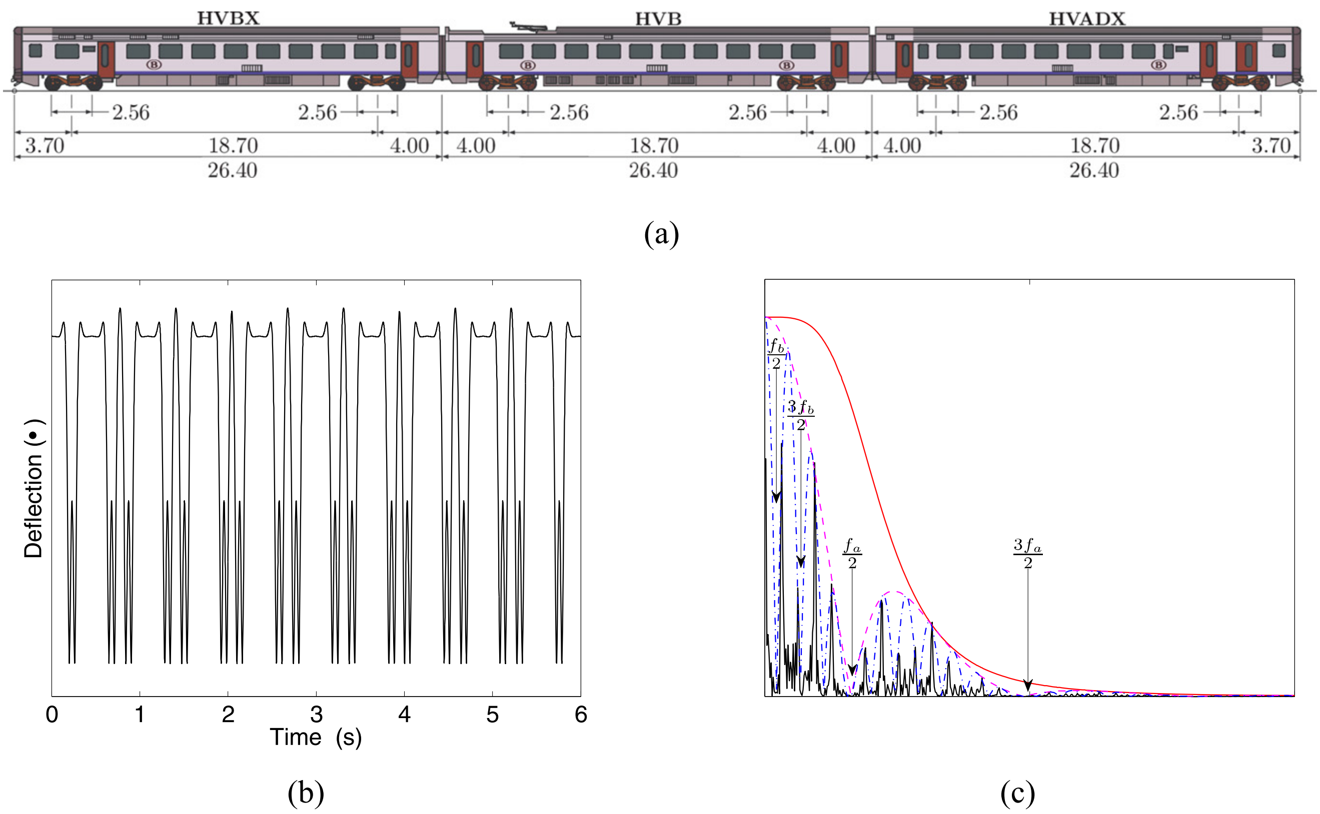


Figure 5. (a) Well-resolved trace and (b) noisy trace of a train circulating at ~50 km h^{-1} measured by the Redondo edge filtering technique.

filter (for instance if they moved due to strong temperature drifts—a temperature change of 50 °C can be recorded in a single day, leading a shift of the Bragg wavelength of ~500 pm) or when the gratings are not well positioned so that the strain transfer is very weak. In this case, the wavelength shifts become poorly encoded into amplitude variations. Figure 5(b) depicts a typical example of noisy trace that was obtained in this case by making a bad connection between the optical fiber containing the FBG sensors and the acquisition system. It confirms that no obvious measurement can be obtained in this case and that it is not possible to evaluate the speed of the train. We will demonstrate in the following that a dominant frequency analysis can efficiently solve this issue.



(a)

(b)

(c)

Figure 6. Theoretical track deflection due to the moving of a nine-carriage AM96 vehicle ($L_c = 26.40$ m, $L_b = 18.70$ m, and $L_a = 2.56$ m) at speed $v = 150 \text{ km h}^{-1}$. (a) Vehicle main geometry for three-carriage unit, (b) time history of track deflection, (b) corresponding frequency content (with envelopes, solid line: single wheel set effect; dash line: single bogie effect; dash-dot line: entire carbody effect).

2.4. Dominant frequency analysis

The spectral content of rail vibration during the passing of a train contains a lot of valuable information. If the main geometry is known (wheel set spacing L_a, bogie spacing L_b and carriage length L_c), it is possible to make the link between three different amplitude modulations in the spectrum of the signal recorded by the interrogator and the vehicle speed v [16]. The geometrical parameters and the modulation phenomenon are illustrated in figure 6.

Periodicities of wheel sets, bogies, and carriages are defined in the frequency domain using the fundamental frequencies

$$f_a = \frac{v}{L_a}$$

$$f_b = \frac{v}{L_b}$$

$$f_c = \frac{v}{L_c}$$

in which the vehicle speed v is assumed to be constant. The presence of peaks with modulated amplitude are due to the beating of frequencies f_a and f_b (zero amplitude at frequencies $\frac{2k+1}{2}f_a$ and $\frac{2k+1}{2}f_b$; $k \in \mathbb{N}$). The fundamental and harmonic frequencies $n\, f_c$ ($n = 1, 2, 3, \ldots$) follow therefore envelopes resulting of this double modulation thanks to L_a and L_b. If the corresponding harmonics are detected, and knowing the dimension of the train, an estimation of the vehicle speed can be done. The method proposed in [17], based on this assumption, was successfully validated using ground vibration measurement. Its principle is based on three successive calculations (figure 7):

(1) A cepstral analysis is firstly performed on the recorded data in order to have an estimation of the vehicle speed as an initial condition for the further steps.
(2) The dominant frequency method is then applied on a smooth signal (using the running root means square or another equivalent smoothing technique) in order to detect the various carriage harmonic frequencies $n\, f_c$ and then to calculate the vehicle speed.
(3) A regression with a simple analytical solution is then conducted in order to better capture the final speed value.

This method has been validated using multiple data generated from prediction models including various virtual conditions of measurement, taking into account external sources other than trains, and sensor response [18]. This automatic train speed calculation procedure is therefore well adapted to FBG signal measurement on the rail.

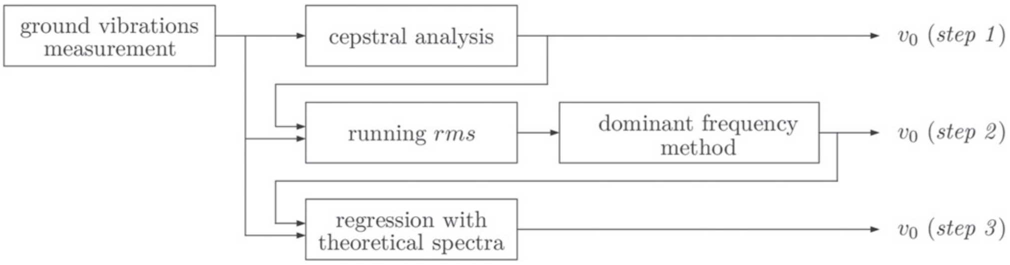


Figure 7. Chart of the automatic procedure for estimating the vehicle speed [17].

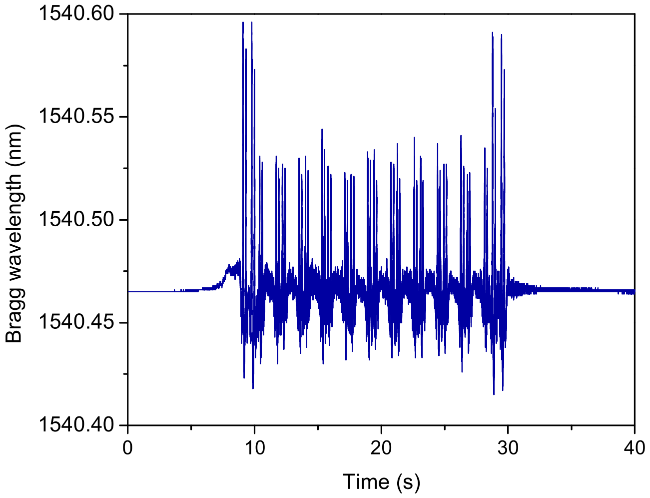


Figure 8. Trace of a train circulating at ~60 km h^{-1} measured by the spectrometer technique.

3. Results

Numerous measurements have been conducted, allowing obtaining relevant statistics on the efficiency of the proposed technique. In this section, to demonstrate its robustness, we compare the speed estimations obtained by our technique (in the case of noisy train signatures for which the procedure described in section 2.4 is applied) with those obtained from the same FBG sensors measured by a spectrometer-based interrogator with high acquisition rate (1 kHz or more). It is important to mention that spectrometer-based commercial solutions at such high acquisition rate are obviously less accurate than their slower counterparts, as the wavelength sampling is typically higher than a few tens of pm. Correlation algorithms are therefore used to improve the actual determination of the Bragg wavelength. Figure 7 displays a typical trace measured by a spectrometer from FBGS Technologies (Model FBG-Scan 800). This device presents an acquisition rate of 2 kHz with an absolute wavelength accuracy of 40 pm. The vertical axis of figure 8 is directly the Bragg wavelength. It can be seen that the positive shifts are high enough to be correctly encoded and therefore detected. This is not the case for the negative shifts that are limited to less than 5 pm and are affected by noise, which is overall present on the baseline of the signal. This slight impairment results from the limited wavelength accuracy of the device. However, in this case, it does not affect the quality of the measurement for axles counting and speed estimation, which can be obtained from the position of the extrema, provided that the train composition is known. This is especially true for gratings glued on the foot of the rail, for which the induced stress is important enough to be properly detected. Let us note that the use of a packaging (essential in real applications) may strongly alter the strain transfer and therefore induce stronger impairments.

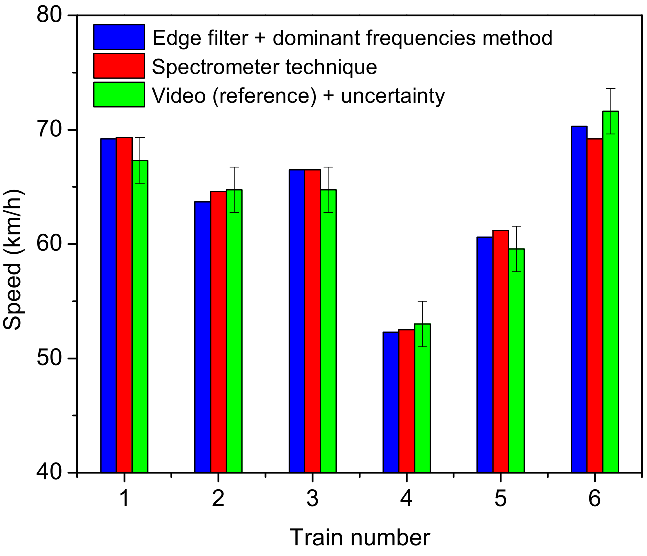


Figure 9. Train speed estimations compared to video recordings for six different trains.

The results provided by these two measurement techniques are also compared to the speed estimation obtained from video recordings. From the processed data presented in figure 9 for six different train configurations, it can be seen that the velocities computed by both techniques fall within the confidence interval of the mean value determined from the camera readout. These results confirm the robustness of the proposed solution, which competes with more expensive techniques. This has to be further confirmed but the proposed method could even solve (at least in some cases) issues arising from rail track FBG detachment. In this case, a good strain transfer is no longer possible so that the train signature might be strongly affected by the noise.

4. Conclusions

In this paper, we have demonstrated that the dominant frequency method can be successfully used to improve the robustness of a commonly used FBG interrogation technique based on wavelength–amplitude conversion dedicated to railway monitoring. For this, uniform FBGs were glued to a railtrack and interrogated by means of the edge filter technique. Then, whatever the noise level on the recorded trace of the train passage by the interrogator, we have experimentally validated that the dominant frequencies method allows obtaining a very good estimate of the train speed, with an error limited to a few % of the actual train speed. The proposed technique therefore competes with more expensive ones that use a spectrometer. Moreover, its inherent high acquisition rate can be compatible for use with very high-speed trains. It is suitable for real-time operation on a CPU that drives the interrogator. Finally, it can be adapted to any dynamic measurement where a periodic modulation of the signal happens.

Acknowledgments

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