FIBER OPTIC SENSING SYSTEM FOR WEIGHING IN MOTION (WIM) AND WHEEL FLAT DETECTION (WFD) IN RAILWAYS ASSETS: THE TWBCS SYSTEM

Antonio IELE[1], Valerio LOPEZ[1-2], Armando LAUDATI[3], Nadia MAZZINO[2], Giovanni BOCCHETTI[2], Antonello CUTOLO[1-3], Andrea CUSANO[1-3]

[1] Optoelectronics Division - Engineering Department - University of Sannio, C.so Garibaldi 107, 82100 - Benevento (Italy) a.iele@unisannio.it; a.cusano@unisannio.it; cutolo@unisannio.it
[2] Ansaldo STS, Via Paolo Mantovani 3-5, 16151 - Genova (Italy)
Valerio.Lopez.ext@ansaldo-sts.com; Nadia.Mazzino@ansaldo-sts.com; Giovanni.Bocchetti@ansaldo-sts.com
[3]OptoSmart s.r.l., Via Pontano 61, 80121 - Napoli (Italy) a.laudati@optosmart.com

Abstract

The aim of this work is to illustrate the design, the development and the full engineering of a novel fiber optic sensing system able to perform weighing in motion as well wheel flat detection in railways assets, and actually included in the product portfolio of Anasldo STS.
In the specific case, we present the main features of the developed system, totally based on the use of FBGs strain sensors suitably clamped to the railways tracks through suitable and certified metallic packages. We show the capability of this system to provide important information about the wheels weight and their defective status in real time and in normal operation means, without requiring the interruption of the railways operability.
Field trials have been carried out along the rails of real scenarios where many of these systems have been successfully installed and verified. In particular we report the installations in Abu Dhabi site (United Arab Emirates) and along the rails of Garibaldi Central Station, in Naples (Italy), and some results which demonstrate the excellent capability of the developed system to achieve the main functionalities of weigh in motion and wheel flat detection with high accuracy.

Keywords: railway, optical fiber sensor, wheelflat detection, weighing in motion, FBG

1 INTRODUCTION

Over the last few decades, rail transport has become one of the most effective means of transporting passengers and goods, and this fact puts major pressure on the infrastructures and therefore innovative maintaining and inspection techniques are required in order to optimize the railway infrastructures availability and increase safety level.
In particular the need of a smart monitoring system, able to perform multifunction diagnostics in railways applications and based on a single technology is very imminent.
Nowdays, railway monitoring requires extensive sensor networks for measuring strain, vibration, temperature, acceleration, and consequently, for developing a monitoring system for these applications, different technologies are required and this is difficult and cost-prohibitive [1,2,3].
In this context, optoelectronic solutions particularly based on Fiber Bragg Gratings sensors (FBG) receive great attention for their well known advantages as easy multiplexing, wavelength encoding and multiparameter sensing, just to name a few.

Many works using FBGs sensors for railway applications have been reported so far [4,5,6,7]. *Tam et al*. shown that a single FBG glued to the rail can provide useful information about the occupation state, the train composition (through axle counting and weighing in motion), its velocity and acceleration [4]. The group of M. Gonzalez-Herraez have demonstrated that, depending on the parameters to be measured, particular orientations and locations of sensors should be considered depending on the measurement function. In doing so, they have achieved the detection of flat wheels [5,6,7]. The Optoelectronics research group of the University of Sannio, since 2008, has demonstrated the efficiency of Fiber Bragg Grating (FBG) sensors to be used as technological platform for railway monitoring and train tracking in transportation applications [1,2,3].
In this work we report our recent efforts to implement a novel fiber optic sensing system for weighing in motion and wheel flat detection in Railways Assets: the so called TWBCS (Train Weight Balance Check System), which is the result of an efficient synergy work involving University of Sannio, Optosmart s.r.l. and Ansaldo STS company.

2 ENABLING TECHNOLOGY

Fiber Bragg Grating (FBG) is a type of distributed Bragg reflector fabricated and embedded inside the optical fiber by means of a UV lithography process. So, it's a segment of optical fiber characterized by a periodic modulation of the refraction index along the axis of the fiber core. Such a grating essentially acts as a band rejection filter in transmission and a band selective mirror in reflection (Figure 1).

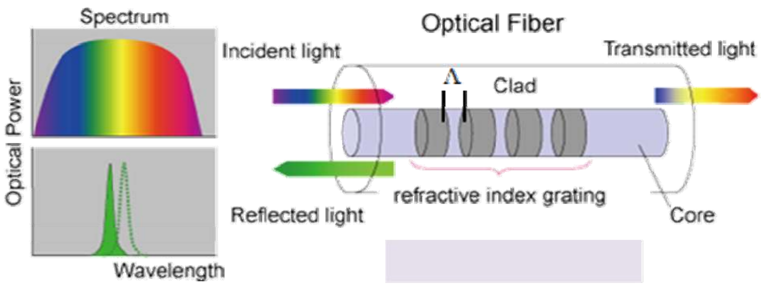

Figure 1: Incident, transmitted and reflected light in a Fiber Bragg Grating.

The back-reflected peak is centered at the Bragg wavelength given by:

$$\lambda_B = 2\, n_{eff}\, \Lambda \quad (1)$$

where n_{eff} is effective refractive index of the transmitting medium, and Λ is the grating period (i.e. the modulation pitch). Since longitudinal strain and temperature modulate both n_{eff} and Λ, the Bragg wavelength undergoes a shift as a result of perturbations of the external medium surrounding the fiber. For a typical grating written in a silica fiber and with $\lambda_B \approx 1550$ nm, sensitivities to strain and temperature are approximately 1.2 pm/με and 10 pm/°C respectively.
In additional to the intrinsic advantages of optical sensors over electrical sensors, such as EM/RF immunity and non-electrical conductive just to say few, FBG sensor technology exhibits many advantages that are particularly suitable for railway applications, such as: entirely passive sensors, multiplexing capability, multi parameter sensing (strain, temperature, vibrations), wavelength encoded, self referencing, small and lightweight, reasonable cost, and many more [8,9,10,11].

3 OPERATIONAL PRINCIPLE

The TWBCS system is based on the FBG technology and on its capability to sense the strain. In the specific case, each FBG sensor, opportunely clamped to the rail, detects the vertical forces generated by the wheel/rail contact and, for each single wheel, returns a wavelength shift usable to obtain a lot of information on the train in transit and on the status of the instrumented rail. To better understand this concept we report in the next picture the typical waveform returned by a single FBG acquired during the transit of a train along the instrumented rail.

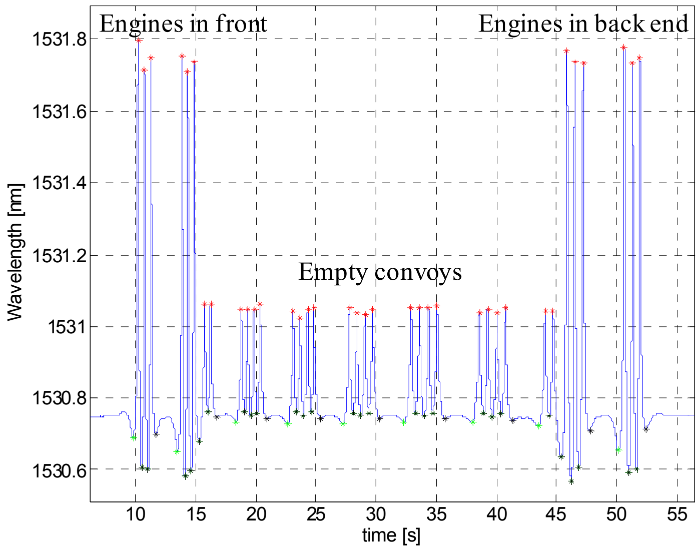

Figure 2: Typical response returned by a FBG clamped to the rail during a transit of a train.

By observing the previous image is noticeable that the single response of the FBG, and in particular the trend of its Bragg wavelength, is characterized by a sequence of pulses, each one associated to the single wheel which composes the train. So, by counting the number of pulses on the sensor response, the FBG can perform the function of axle counter and it is a good alternative to the conventional axle counter. In addition, if is known the physical distance between two adjacent wheels, the speed and the acceleration of the convoy is calculated. If the composition of the train in transit is unknown, by placing only two FBGs along a short length of track, we can detect the timing when the axle passes through them and we can calculate the train speed.

Besides, the amplitude (or the wavelength shift) of each pulse depending by the load applied on the wheel: in fact, as can you see in the Figure 2, the pulses related to the wheels of the engines (in front and in the back end) returns the largest wavelength shift than the pulses of the empty convoys, and this is explained by the fact that the engine presents both the load of the motor and that of the tank with the fuel, and so, it's a heavy convoy. For this reason, FBGs clamped to the rails can be used to measure the weight distribution for wheel and for wagon, and detect any unbalance along the train in movement.

In our case, the FBG strain sensors, through a judicious data processing, are also able to provide important information about the defective status of the wheels in real time, and without requiring the interruption of the railways operability. In fact, as shown in the Figure 3, we split the original signal returned by the single FBG sensor (Figure 3a) in two main components: a so called static component (Figure 3b), which is the output of a Low Pass Filtering, and a dynamic component (Figure 3c), which is obtained by applying a High Pass Filtering to the raw sensor signal.

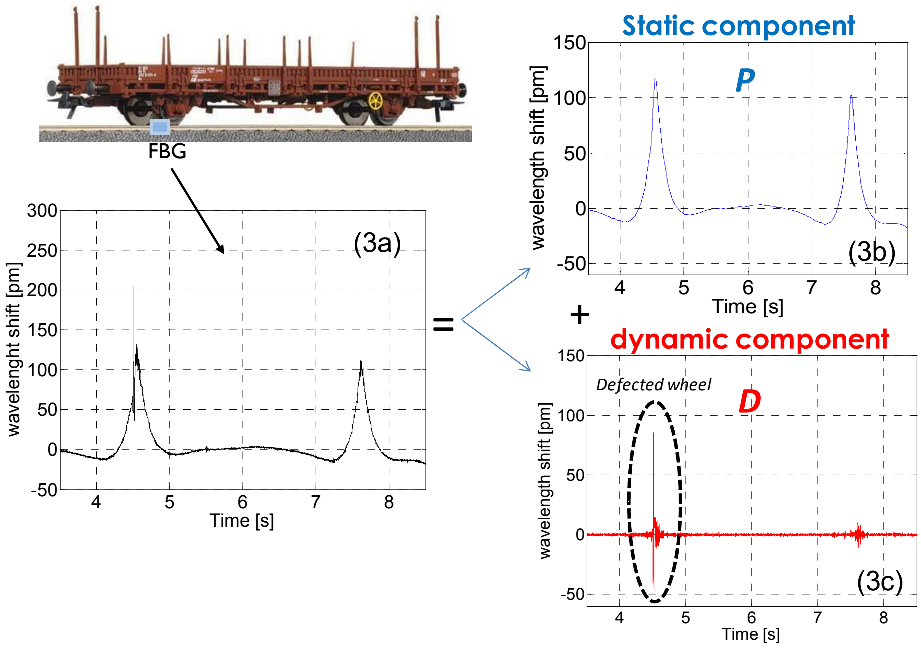

Figure 3: Raw FBG sensor signal (3a), static (3b) and dynamic (3c) component.

If the wheel is defected, on the dynamic component retuned by the FBG is clearly visible the presence of a particular feature produced by the impact of the defect on the rail. Using this feature, the system is able to measuring the rolling surface's quality of each wheel.

4 ARCHITECTURE AND INSTALLATION

The typical system and installation layout of the TWBCS is shown in the following Figure 4.

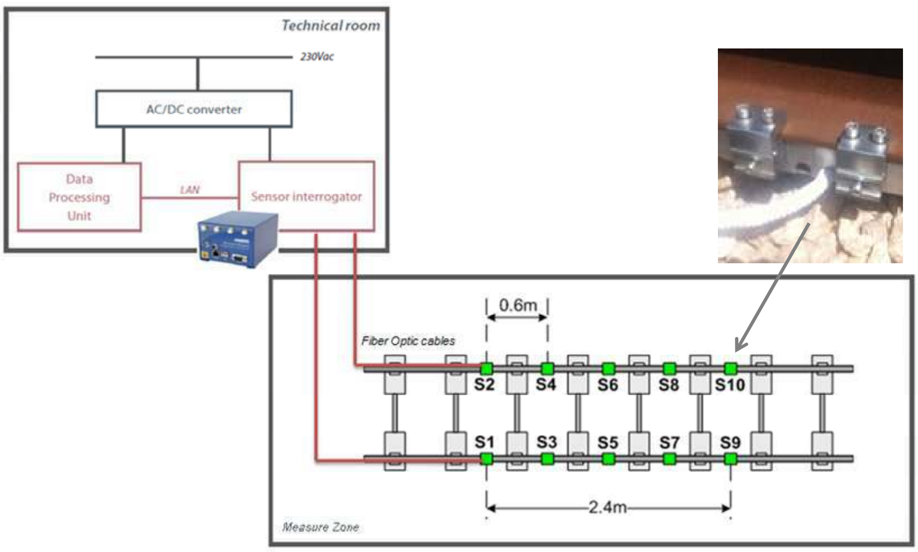

Figure 4: TWBCS typical installation layout

The Measure Zone is composed by ten optical fiber sensors (five for rail spaced of zero point six meters), which detect the vertical forces generated by the wheel/rail contact: they are installed on a track section, parallel-distributed along both rails. In the Technical room, near the rails, are located the sensor interrogator and the data processing unit which acquires the signals returned by the sensors and processes them in real time. Fiber optic cables ensures the connection between the sensors and the interrogator unit.

4.1 FBG sensor and packaging

The TWBCS sensor is a FBG packaged strain sensor, placed in robust metal housing and mounted under the rail (between two sleepers), to improve robustness features, thereby allowing to use it in harsh operating environment. A typical drawing is shown in the following Figure 5.

Figure 5: TWBCS sensor

The mounting takes only few minutes and no special preparation of the rail is required. The installation doesn't require modification of existing track structure and no specific foundation is needed. For this reasons, the system ensure a fast and non invasive installation (no drilling and no gluing operations are required) and the innovative technology and design of the sensors give to sensor further several advantages, such as: minimal impact on normal track maintenance, withstand and usable in harsh conditions (temperature, humidity, vibration, dust, sand), no electric power supply and electric equipment near the rail, fiber optic cabling, no galvanic connection to the rail. Also, it's in compliance with the standards EN50125-3 and IS402 (the certification tests conducted in ACCREDIA laboratories have been successfully overcome).

4.2 Interrogator Module

The interrogator system used to detect the light reflected by all the FBGs installed along the rail, and the Bragg waveleghts trend when a train passes on the instrumented rail, is an ultra compact and robust interrogator for dynamic measurement of FBG sensors. In Figure 6 is shown the architecture of this system.

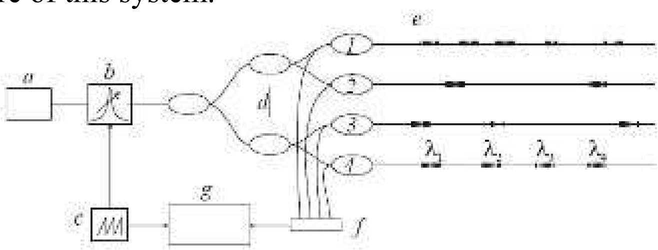

Figure 6: Interrogator scheme: a) optical source, b) filter scan, c) sweep generator, d) splitter, e) FBG, f) photo detectors, g) processor.

It is composed by a tunable laser source that enables high-resolution interrogation at multi-kHz frequencies, a filter scan (used to create the timing between source and receiver), a sweep generator, a splitter used to split the source signal to all the channels, a photo detectors, and a processor unit. The frequency used to interrogate simultaneously all the FBGs is 2.5 kHz, and the repeatability is less than 1 pm.

4.3 Installations in real scenarios

After the stage of design and development of the TWBCS, we have carried out a lot of field tests, to validate both the hardware and the software developed. Here we want only to report the final installations of the measuring systems, in two real scenarios: Abu Dhabi railway, in United Arab Emirates, and Naples (Italy) along the rail of EAV Garibaldi central station. In the first case, thanks to a tender won by Ansaldo STS, we have installed and tested three Weight In Motion (WIM) systems; instead, in Napoli, thanks to an Italian National Project (PON-SICURFER, Tecnologie innovative per la SICURezza della circolazione dei veicoli FERroviari), we have installed and verified the first prototype of WIM and Wheel Flat Detector (WFD) system. The experimental results and the discussion abuot the performance exibits by the system for both weight in motion and wheel flat detection functionalities, are shown in the next section.

Figure 7: WIM system prototype and WIM sensor along Abu Dhabi railway

Figure 8: WIM - WFD system prototype along the rail of Garibaldi central station

5 EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section we show the experimental results returned by the TWBCS system for the main functionalities WIM and WFD. In particular, we present the typical waveforms returned by the FBG sensors clamped to the rail during a passage of a train in normal operation, the calibration procedure and the main features of the data processing software developed. In addition, we show the results achieved during functional verification tests of the WIM-WFD system installed along the rails of Garibaldi Central Station in Naples (Italy).

5.1 WIM functionality

As we said previously, the FBG clamped to the rail can be used to measure the weight for wheel because the shift of Bragg wavelength is related to the weight on each wheel in transit over the rail. During a lot of field tests we have defined and developed a calibration tool, which take in input the wavelength shift and the weight of the engines (or wagons with know weight), and returns the so called calibration coefficient (or sensitivity coefficient) for each FBG, which is used to convert the strain measurements (or the wavelength shifts) in weight. Here we report the results returned by the system installed in Garibaldi central station (EAV railway, Naples). The calibration of each FBG sensor has been carried out by using empty passenger trains and their total nominal weight. In particular, along the railway of EAV runs only three type of trains, which are: ETR Metrostar, ETR T21 Type, and ETR FE220 Type. Using a RFID system (used to control the railway traffic by EAV company) we have correlated the data files returned by WIM-WFD system with the type of ETRs passed on the instrumented rails. On the response returned by each FBG installed along the rail, after the Low Pass filtering, we calculated the amplitudes (or the wavelength shift) of the pulses, as shown in the next picture.

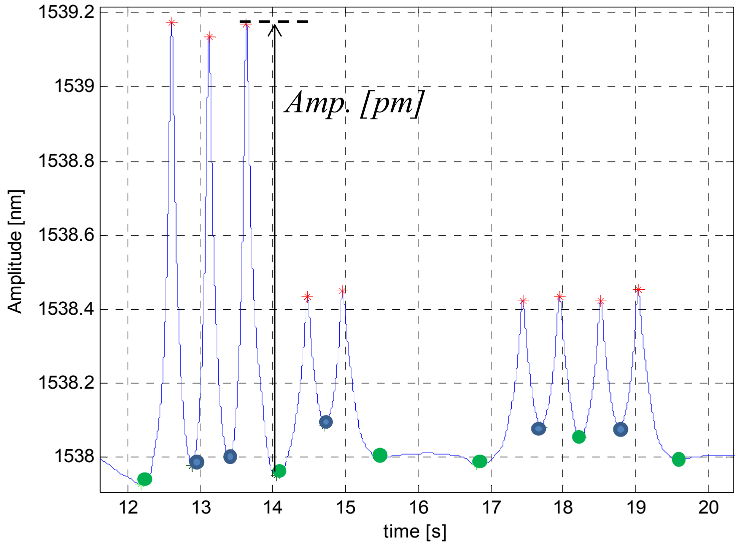

Figure 9: FBG response and wavelength shift related to the weight force

So, for each FBG, we have correlated the sum of all the amplitudes (or wavelength shifts) and the total half nominal weight. In the following table we reports the repeatability and the sensitivity (or calibration coefficient) exibits by the sensors installed along the EAV rails, using the information returned by 26 ETRs FE220 Type.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Medium Amplitude [pm]	1798	2326	1790	1806	1680	1845	2012	1695	2769	1762
Standard Deviation %	3.2	1.8	2.6	2.0	3.2	2.3	3.4	2.5	2.6	3.3
Alfa coefficient [kg/pm]	15.5	12	15.6	15.5	16.6	15.1	13.9	16.5	10.1	15.9

Table 1: Medium amplitudes, standard deviations %, calibration coefficients - EAV system

The sensors labelled with odd number are installed along the left rail, instead the sensors labelled with even number are clamped to the right rail. All the sensors exhibits a repeatability less than 4 %, and, in addition, each FBG is self referred and returns a sensitivity which take into account the mechanical state of the rail in the sensor position. Using the alfa coefficients, we have tested the WIM functionality, thanks to load tests on ETRs in normal operation (Empty ETRs or ETRs with passengers); the obtained results are shown in the next picture.

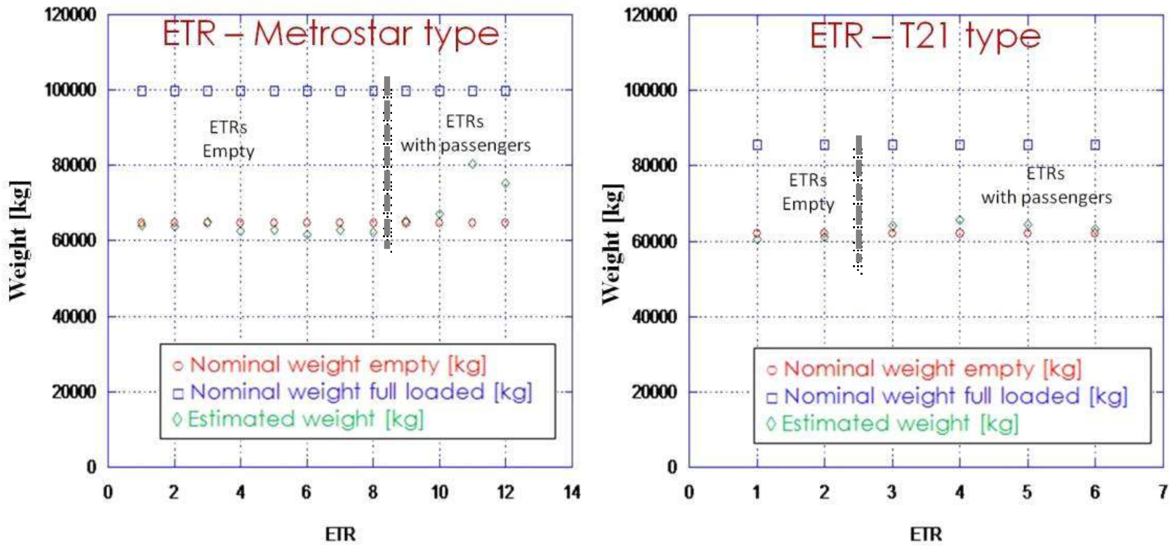

Figure 10: Weight tests on ETR in normal operation (Empty ETRs or ETRs with passengers)

As shown in the previous Figure 10, we have compared the estimated weight for 12 ETRs Metrostar Type and 6 ETRs T21 Type, to the nominal weight empty and to the nominal weight full loaded. For the empty trains the estimated weight is very closed to the nominal weight, and the accuracy returned by the system is less than 2 per cent. In addition, the values of estimated weight for the ETRs with passengers, are correctly included in the range empty-full loaded nominal weight.

5.2 WFD functionality

For this functionality we use the so called "Dynamic component", which is obtained by applying a High Pass Filtering to the raw signal returned by each FBG clamped to the rail foot. In particular each sensor is used to monitor a portion of the rolling surface of each wheel, with a lenght equal to the region of influence of each sensor: ie 0.6 meters. The reconstruction of the profile of each wheel is obtained by the "merging" of the five dynamic responses returned by the five FBG sensors (in their respective regions of influence), ensuring the monitoring of 5 * 0.6 meters = 3 meters of length of running surface.
If on the running surface there is a defect, the "dynamic signal" returned by the entire array provide a particular feature which also depends by the weight on the wheel (static component) and by the point of impact of the defect along the rail. So, we have developed a judicious tool which normalize the dynamic component respect to the Static component and also take into account the impact point.
So, the signal processing returns a normalized waveform (arbitrary unit) for each wheel, composed by a sequence of five so called Vibrational levels (one for each section of circumference monitored by the single FBG sensor) as shown in the next picture.

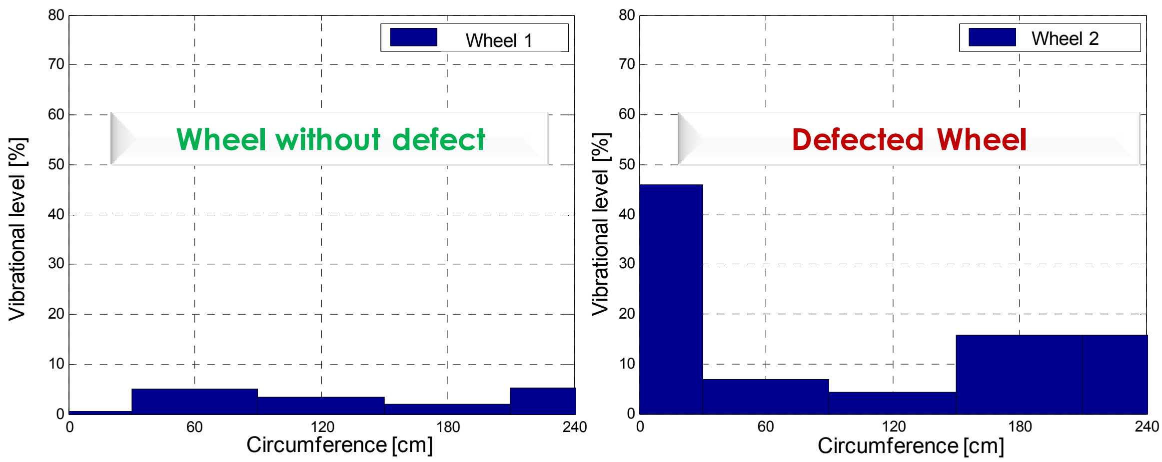

Figure 11: typical example of vibrational levels for defected wheel and for wheel whitout defect

Comparing the vibrational levels with a threshold defined during the calibration stage and based on the passage of trains with new wheels, the system is able to detect a defected wheel and to generate an alarm. In the following picture we show the threshold level returned by the system for about 180 new wheels (ETRs Metrostar Type) passed over the instrumented rails. The Defect Indicator returned by each wheel corresponds to the maximum vibrational level measured on the normalized signal.

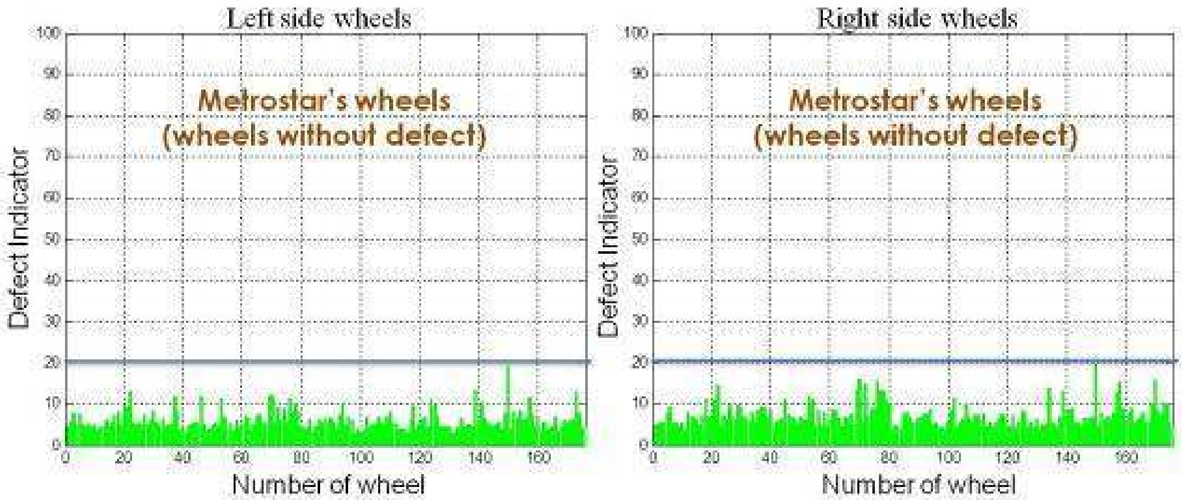

Figure 12: threshold value for new wheels

Thanks to the collaboration of the EAV staff, we have also carried out experimental trials to validate the WFD functionality. In the specific case we have compared the system's results (Defect Indicator for wheel) and the scanner laser measurements on the rolling surfaces of wheels of EAV test train, and as shown in the next figure, the system's result are in agreement with the measurements returned by the scanner laser probe.

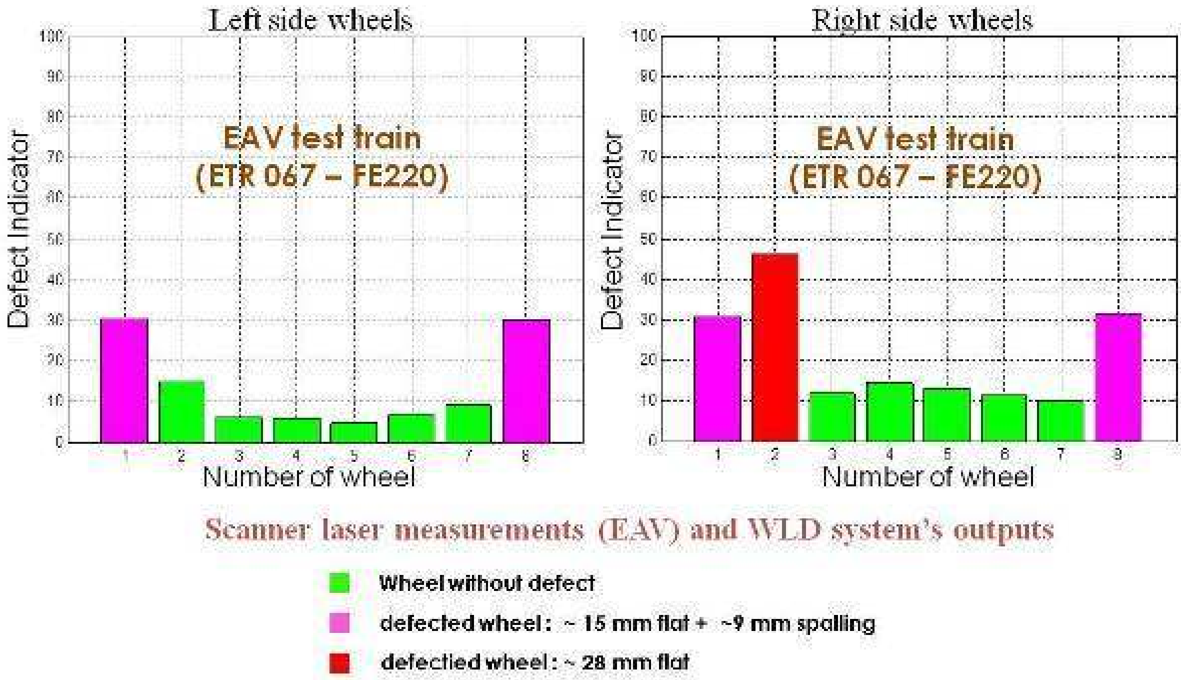

Figure 13: WFD functionality. Comparison between the system's results (Defect Indicator for wheel) and scanner laser measurements on the rolling surfaces of wheels of EAV test train

6 CONCLUSIONS

The Optoelectronics Research Group at the University of Sannio, in tight collaboration with Ansaldo STS company and the Optosmart srl, has developed a novel photonic sensing system for Smart Railway, actually included in the product portfolio of Anasldo STS.

This work showed the main features of the developed system and its capability to provide important information about the wheels weight and their defective status in real time and in normal operation means, without requiring the interruption of the railways operability. Experimental trials demonstrated the correct operation of the WIM and WILD functionalities. The WIM accuracy is less than 2 %. Instead, the tests related to the WFD funcionality demonstrated the great capability of the system to detect and to measure any defected wheel: the defective index (or Defect Indicator) returned by the system for a defected wheel has a value greater than the value produced by wheels without defects, and with an amplitude (or Level) related to the size of the defect.

REFERENCES

[1] A. Laudati, G. Lanza, A. Cusano, A. Cutolo, M. Giordano, G. Breglio, A. Antonelli, Railway monitoring and train tracking by fiber brag grating sensors: a case study in Italy. *Proc. of 4th EWSHM*. ISBN: 978-1-932078-94-7 (2008).

[2] A. Cutolo, A. Cusano, F.A. Bruno, A. Iele, A. Laudati, G. Parente, M. Giordano, G. Breglio, N. Mazzino, G. Bocchetti, Weigh in motion using Fiber Bragg Grating sensors: An industrial case in Italy. *5th EWSHM* (2010).

[3] A. Cusano, A. Laudati, A. Iele, F. A. Bruno, G. Parente, M. Giordano, N. Mazzino, G. Bocchetti, Smart Railways in Italy. *3th APWSHM* (2010).

[4] 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, K.Y. Lee, A fiber Bragg grating sensor system for train axle counting, *IEEE Sensors Journal*, **10**, 1905-1912, 2010.

[5] M.L. Filograno, P. Corredera, A. Rodriguez-Barrios, S. Martin-Lopez, M. Rodriguez-Plaza, A. Andres-Alguacil, M. Gonzalez-Herraez, Real time monitoring of railway traffic using fiber Bragg grating sensors. *IEEE Sensors Journal,* **12**, 85–92. 2010.

[6] M.L. Filograno, P. Corredera, M. Gonzalez-Herraez, M. Rodriguez-Plaza, A. Andres-Alguacil, Wheel flat detection in high-speed railway systems using fiber Bragg gratings. *IEEE Sensors Journal,* **13**, 4808–4816, 2013.

[7] G. Kouroussis, C. Caucheteur, D. Kinet, G. Alexandrou, O. Verlinden, V. Moeyaert, Review of Trackside Monitoring Solutions: From Strain Gages to Optical Fibre Sensors. *Sensors*, **15**, 20115-20139, 2015.

[8] A. Cusano, A. Cutolo, J. Albert. *"Fiber Bragg grating sensors: recent advancements, industrial applications and market exploitation"*, Bentham Science Publishers ISBN: 978-1-60805-343-8 (2011).

[9] K. O. Hill, G. Meltz, Fiber Bragg grating technology fundamentals and overview. *Journal of lightwave technology,* **15**, 1263-1276, 1997.

[10] Y.J. Rao, In-fibre Bragg grating sensors. *Measurement science and technology,* **8**, 355–375, 1997.

[11] A.D. Kersey, M.A. Davis, H.J. Patrick, M. LeBlanc, K.P. Koo, Fiber grating sensors. *Journal of lightwave technology,* **15**, 1442–1463, 1997.