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Innovative FBG sensing techniques for the railway industry: Application to Overhead Contact Line Monitoring

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ABSTRACT

Current collection is a key issue in modern electrical railway, and its performances are mainly determined by the pantograph/catenary interactions. Whilst being the less investigated topic, the pantograph/catenary mechanical interface is the most crucial one. Many incidents and traffic interruptions are due to degraded, or even damaged, electrical contacts between current collectors and contact wires. During the 6th European Framework Program (FP6) CATIEMON project (*CATenary InterfacE MONitoring*), both FBG-based sensors and systems dedicated to the pantograph/catenary interaction monitoring - directly from the high voltage contact wire - have been developed and tested. This paper describes their design and installation but also results coming from field-tests. It highlights their advantages for the railway stakeholders and end-users in term of train operation enhancement.

Keywords: Fibre Bragg Grating, Optical Fibre Sensor, Monitoring, Instrumentation, Railway, Pantograph, Catenary.

1. INTRODUCTION

By 2020 the European rail networks should be handling three times the present freight and passengers levels. The market share of rail sector for passengers and freight should also double in the same time. These figures clearly highlight that efficient and safe railways are mandatory to guarantee sustainable mobility in Europe. In order to cope with future demands on railway transportation, the European Union (EU) has developed strategic initiatives and has launched research programs in order to enhance the rail competitiveness [1]. Among other aspects, seamless passenger/freight transport and interoperability of infrastructures become essential in a deregulated market. In such a context, the CEA LIST takes part to the CATIEMON European Research Project (*CATenary InterfacE MONitoring*) [2] which is driven by SIEMENS and involves major stakeholders of the European railway sector such as rolling stock operators, infrastructure managers, overhead systems makers, inspection companies, measurement systems providers and research institutes[1]. The CEA LIST has to develop optical fiber sensing techniques based on Fiber Bragg Grating (FBG) transducers in order to characterize the pantograph/catenary mechanical interactions [3, 4]. Such measurements are gathered and interpreted to optimize railway infrastructures maintenance and availability. This paper describes several innovative sensors realized and tested. Then dedicated interrogation units are presented. Lastly, the results of several field tests conducted during the course of the project are described and commented with respect to the end-users needs.

2. THE "*INSPECTION GATE*" CONCEPT FOR RAILWAY TRAFFIC MONITORING

To avoid traffic interruptions and heavy maintenance actions due to operational incidents at the pantograph/catenary interface, an innovative concept of Inspection Gate has been designed and developed by the consortium of the CATIEMON project. Such a control gate is permanently localized at a strategic point of a rail network. It includes several kinds of sensors and monitoring systems in order to characterize the current collectors' impact of any train entering the network. In fact, badly adjusted pantographs and/or damaged current collectors are source of incidents. Indeed, a too strong contact force induces an excessive wear on the contact line and may cause damages to the infrastructure. On the contrary, a too weak contact force generates electric arcing when loosing the contact - damaging the pantograph's carbon strips as well as the contact line – and in the same time induces fluctuations to the electrical current transmitted to the motors, limiting the train speed. Detecting high/low uplift and strain levels along the contact wire can be performed by the FBG-based sensors. Integrated into an automatic alert system, these sensors and their

[1] CATIEMON consortium includes: Siemens (Ge), BLS (CH) and ÖBB (Au) two railways company, Furrer&Frey (CH) and Cybernetix (Fr) as equipment providers, Morganite (UK) Carbon strips and pantoheads manufacturer, plus IPHT (D) and the CEA LIST (Fr) two R&D Institutes.

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associated monitoring stations aim at protecting both the infrastructures and the rolling stocks. By estimating the impact of any train entering a given network, they help infrastructure managers to reduce the risks of incidents on their rail grid (for instance in tunnels) and to reduce their maintenance costs. The CEA LIST has developed several FBG-based sensors (uplift sensor based on FBG displacement measurement, FBG impact sensors, and quasi-distributed strain measurement of contact lines based on several FBG chains directly glued along the copper wire) and FBG demultiplexing units. Using this FBG sensing technology makes it possible to characterize the pantograph/catenary interaction directly "from the wire", *e.g.* as close as possible to the mechanical interface itself.

As a first prototype, the Inspection Gate developed within the CATIEMON project includes several measurement technologies such as a rangefinder laser for 1D uplift measurement, a laser scanner coupled with a camera for a two dimensional uplift measurement (vertical & horizontal), but also FBG-based impact and 3D displacement sensors, and FBG strain sensors. From experience feedback, FBG-based metrology appears to be the only technology able to perform the complete set of required measurements, as specified by the project's end-users, namely the 3D uplift (FBG triangulation sensor) of the contact line, and the distribution of strain along the contact wire. An existing steady arm (used to define the contact wire's position with regard to the rails) was also instrumented with FBGs for hit detection. Usual advantages of FBG sensors such as electro-magnetic immunity, high sensitivity, low intrusivity, robustness for outdoor installation/operation and remote interrogation were essentials for this application. Figure 1 illustrates the location of these FBG sensors on the Inspection Gate.

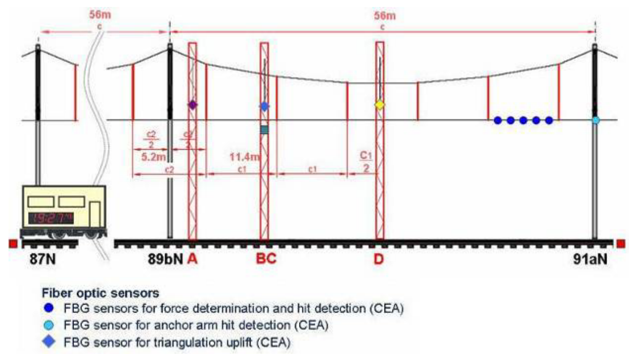

Fig. 1: Inspection Gate including FBG sensors and remote systems

3. FBG SENSORS/SYSTEMS FOR PANTOGRAPH/CATENARY MONITORING

Three kinds of FBG-based sensors were developed and implemented as part of this first Inspection Gate's prototype.

3D displacement sensor. Three FBG-based displacement sensors are mounted at the summits of a triangular and rigid metallic frame installed above the contact wire, while their mobile extremities are attached together at a single point on the contact wire (Fig. 2a). Each displacement sensor comprises a mobile rod linked to springs transmitting the rod's displacement to a test piece incorporating a FBG strain transducer. Springs and FBG-based transducing element are designed in order to cope with the elastic limit of the optical silica fiber and to the mechanical resistance of photo-induced FBGs. A calibration curve is established for each displacement sensor in order to convert the strain measurement into a displacement. A 20 cm range is required for this application, corresponding to a 1 nm spectral shift of the Bragg wavelength. Then, basic trigonometric relationships are used to convert in real time the measurement of these three displacement sensors into a 3D trajectory of the contact wire's point under investigation.

Instrumented steady-arm. A FBG transducer is located in a V-groove machined into the metallic cylindrical arm of a steady arm (Fig. 2b). Then the FBG transducer is prepared in laboratory and glued within this groove. An optical fiber transmission cable is positioned in order to remotely interrogate the instrumented steady arm. In operation, this steady arm is bended in response to contact wire's displacements (especially when a pantograph is passing under). This bending in turn induces a wavelength shift of the Bragg peak. Such a sensor is used to detect hits due to any corrugated pantograph passing through the Inspection Gate and thus inducing high frequency vibrations along the contact line.

FBG strain sensor chains. Measuring the mechanical strains caused by the pantograph/catenary interaction at several locations along the contact wire is particularly useful in order to evaluate the current collection's quality. Such quasi-distributed strain measurements are correlated for instance to the contact force applied by the pantograph to the contact line. High (resp. low) contact forces are detected as high (resp. low) strain levels along the contact line. Both may caused an excessive wear of the copper's wire, so detection of such events is mandatory to prevent potential incidents. Moreover, quasi-distributed strain measurements along the whole gate's length and repeated over many commercial trains are useful to establish a distribution of the strains induced by trains on the infrastructure. Once high and low limits have been defined on such a distribution, the presence of any train passing the Gate and inducing strain level out of these limits should be immediately reported to the infrastructure management. A message could then be sent to the involved rolling stock operator in order to carry control and maintenance on its train. As an ultimate option, the train can also be stopped if there is a high risk for the infrastructure to be seriously damaged. To perform the sensing function, four strain sensor chains, each one including up to 20 spectrally multiplexed FBG transducers spaced by either 25 cm or 50 cm, were glued, thanks to a dedicated protocol (Fig. 2c), along several sections of contact lines.

FBG interrogation units. All these FBG-based sensors are interrogated using a high-performance multi-channel demultiplexing system recently developed by the CEA LIST and called *BraggFIT³* (Fig. 2d). This interrogation unit includes six optical channels monitored in parallel at 1 kHz acquisition frequency over a 30 nm wide spectral window centered at 1.55 µm, and provides a spectral accuracy better than 1 pm. Each optical channel incorporates a carefully designed transimpedance circuit which gain is independently controlled by software through an FPGA board. An adjustable dynamic of more than 40 dB (in term of optical power) is available. The signal-to-noise ratio has also been improved thanks to an Erbium-Doped Fiber Amplifier (EDFA). This optoelectronic system and its software interface have been designed using a client/server approach. On field, a notebook (the client) is used to configure the monitoring system (the server) equipped with network modules (Ethernet and WiFi). When needed, any authorized user can thus get remotely connected with the monitoring system in order to change parameters, check the acquisitions or retrieve data. This is particularly useful for railway applications where the systems are located close to the tracks: one gets connected to the system without disturbing the commercial traffic.

In addition to this high-performance FBG interrogator, a compact, hand-held and autonomous monitoring system has been integrated by the CEA LIST and used during the sensors installation periods. The so-called *BraggLight* system realizes the FBG spectral analysis at a scan rate up to 200 Hz. It is made up of a compact box connected to a laptop. Communications with the PC as well as the power supply are made by means of a single USB link. With such basic approach only one optical channel can be checked, but multi-channel versions are also possible using an integrated optical switch. Thanks to this useful portable instrument, the installation of the FBG sensors was constantly monitored while neither transmission cables nor power supply was available on-site at that time.

Fig. 2a: FBG-based tripod for 3D displacement sensing

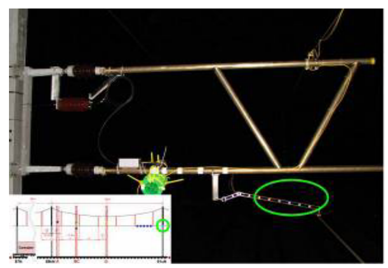

Fig. 2b: FBG glued on steady arm, above the contact line

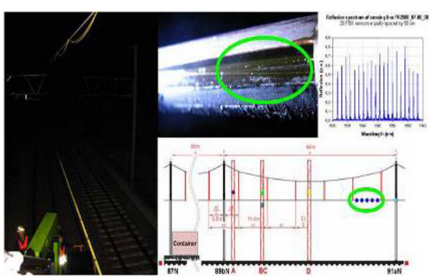

Fig. 2c: Multiplexed FBG chains glued on the contact wire

Fig. 2d: Remote *BraggFIT³* monitoring system

4. SENSORS/SYSTEMS INSTALLATION AND FIELD TESTS

Installation. FBG sensors and systems, as part of the whole Inspection Gate, have been installed in Switzerland some weeks before the opening of a new tunnel running under the Swiss Alps: the Lötschberg tunnel (34.6 km in length, open since June 15th, 2007). As only one tube is fully operational along the standard length of this tunnel, it constitutes a strategic location where incidents must be avoided. The sensors installation was performed by night (with all trains transferred to the adjacent track) in order to minimize perturbations to the commercial traffic. Specific mounting procedures were adapted to outdoor working conditions (night, cold, wind, weather), especially for gluing the FBG strain sensor chains on the contact wire. In practice, these sensing lines were glued using a single-component UV-light cured epoxy and a fibre pigtailed UV lamp. The *BraggLight* monitoring system was used to check in real-time the FBG gluing.

Field tests. Two kinds of tests were performed during the project. First, a locomotive equipped with several types of pantographs, each one adjusted with given contact forces, was used to calibrate the sensors with respect to both train speed and contact force. This test aimed at finding a relationship between the measured parameters (contact wire's displacement and strain) and the input parameters (contact force, speed). Speeds ranging from 5 km/h to 100 km/h (maximum speed authorized at the Inspection Gate's location) were investigated. At each speed level, several contact forces were analyzed: 50 N, 70 N and 90 N. A linear relationship was found between the measured strain along the wire (averaged over all the FBG strain sensors of a given sensing chain) and the train's speed at any given contact force (Fig. 3a). For two contact forces, the slope of this linear fit is found to be different. Plotting these slopes (in pm.km^{-1}.h) with respect to the tested contact force, a linear fit could also be derived (Fig. 3b). Thanks to such calibrations, knowing the speed of any new train entering the network is enough in order to retrieve the contact force from the measured strain values. These results may also be used to extrapolate the impact of the train at other locations of the rail network where the speed may differ. In our case, the train direction is also an input parameter as the gate is located nearby to a curve: thus the mechanical behavior of the contact wire changes from one train direction to the other.

In parallel to such calibration runs, measurements were also collected on commercial trains (both passengers and freight) running under the Inspection Gate. Concerning the FBG sensor chains, the strain was averaged over all the FBGs (thus over all the sensing points along the contact wire). To do so, the local strain resulting from any current collector (two per pantograph usually) is detected for each sensor. These results are then processed to draw the distribution (histogram) of the measured strain averaged over the whole gate's section (Fig. 3c). By comparing the averaged strain associated to any new train passing the gate with this distribution, it is possible to estimate its potential impact on the railway infrastructure. But to do so, high and low limits have to be carefully defined by the infrastructure management rules: too strict thresholds may lead to stop too many trains while in the reverse the infrastructure is not protected enough.

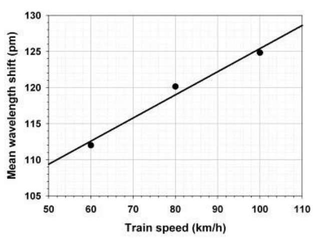

Fig. 3a: Wavelength shift ($\propto$ strain) *vs.* train speed at a contact force of 92 N

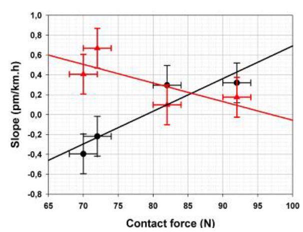

Fig. 3b: Fitted slope *versus* contact force for both train directions (distinguished on the plot by the red and black colors)

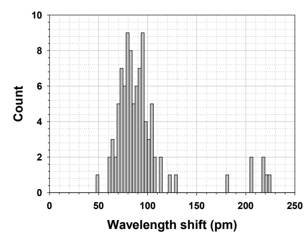

Fig. 3c: Histogram of the wavelength shift ($\propto$ strain) for 100 tested trains

5. CONCLUSION AND PERSPECTIVES

Several innovative electromagnetic immune optical FBG sensors and two interrogators suited to railway applications have been developed and intensively tested during the CATIEMON European research project. In addition to in-lab design and tests, these sensing equipments have been installed for several field tests on commercial lines dispatched over an eighteen months long period. FBG sensors, able to sustain High Voltage at railway infrastructures as well as outdoor conditions, and efficient installation procedures have been developed and validated. Data acquired during the course of the project have shown that FBG-based sensing is a promising approach in order to characterize the pantograph/catenary interactions. This technology provides new diagnosis tools to the end-users in order to improve railway infrastructures' management procedures, to increase safety and thus availability. It may now benefit to all railway stakeholders in order to face the increasing demand for railway transportation, in particular in Europe.

REFERENCES

1. L. Maurin, P. Ferdinand, G. Laffont, N. Roussel, J. Boussoir et S. Rougeault, « *High speed real-time contact measurements between a smart train pantograph with embedded fibre Bragg grating sensors and its overhead contact line* », Structural Health Monitoring, Vol. 2, pp 1808-1815, 2007
2. http://www.catiemon.com
3. S. Kusumi, T. Fukutani & K. Nezu, « *Diagnosis of Overhead Contact Line based on Contact Force* », QR of RTRI, vol. 47, n° 1, pp. 39-45, 2006
4. Yong Hyeon Cho, « *Numerical simulations of the dynamic responses of railway overhead contact lines to a moving pantograph, considering a nonlinear dropper* », Journal of Sound and Vibration, vol. 315, pp. 433-454, 2008.