High performance Fiber Bragg Grating systems for Smart Structures: Application to Overhead Contact Line monitoring in the railway industry

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ABSTRACT

Enhancing train transportation remains a key issue since transportation means are gradually becoming saturated in capacity in modern countries. Therefore, the European Union (EU) develops initiatives to enhance the rail grid competitiveness, by means of deregulation and interoperability, and supports this process with an existing rail network planned upgrade.

In such a context, the 6th European Framework Program (FP6) CATIEMON project (*CATenary InterfacE MONitoring; 2005-2009)*, has been specifically devoted to the development of instrumentations and sensors able to 'control' any train entering a railway network. This was achieved by monitoring the interaction between the train pantograph and its Overhead Contact Line (OCL) at a standing location: a *control gate*, equipped with permanently controlled sensors.

Several solutions have been simultaneously evaluated, including different kinds of sensors and measurement systems. The electromagnetic-immune Optical Fibre Bragg Grating (FBG) sensing technology developed by CEA List has demonstrated, within this project, fully relevant, reproducible, and exploitable measurements for the infrastructure manager.

To do so, we have been working on the entire FBG instrumentation, including the development of innovative sensors, as well as the set-up of two proprietary measurements units. The first one, lightweight, small-form factor one: *BraggLight*, proved on field to be very handy to work in 'acrobatic' and bad weather conditions for FBG sensor lines control during their installation on the OCL. The second one, *BraggFit*^{3}, with high-end performances, devoted to high-speed and very accurate Bragg wavelength measurements (resolution and precision better than 1 pm at 1 kHz full speed in parallel on 6 optical lines) for permanent monitoring purposes.

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Such developments enable today the infrastructure managers to control the rolling stock operators' compliance with their specific regulation procedures (*e.g.:* authorized maximum wear on the OCL), and allow them to stop any train identified by the control gate to potentially damage their infrastructure. More generally, the FBG sensors and systems developed at CEA List can be used in many industrial sectors, including transportation (railway, marine, aeronautics) but also civil infrastructures (bridges, buildings, power plants, underground…), as well as oil & gas industry, for structure monitoring and smart structure purposes, and are particularly well-suited in harsh environments where non-intrusive high-speed sub-picometric (~ 0.5 µm/m or 5/100°C at 1 kHz) Bragg wavelength accuracy and resolution are required.

STATE-OF-THE-ART OF FBG MEASUREMENT SYSTEMS

The most straightforward mean to interrogate a FBG transducer is based on broadband source illumination (using a broadband light source such as an ASE – *Amplified Spontaneous Emission* – source or a SLED – *Super Luminescent Diode* – source) whose narrow-band reflected peak is directed into a wavelength detection system. Several methods exist to measure the wavelength shift of the sensor including a miniaturized spectrometer, a wavelength tuneable pass-band filter, an interferometer or an edge filter. Each method presents advantages and drawbacks with respect to the basic requirements of a high-performance FBG monitoring system. CEA List has already developed interrogation units using many of these techniques. Using a widely tuneable source, such a system has reached sub-picometric spectral resolution over a range of 30 nm on the telecom C-band (@ 1.55 µm). Six measurements channels were available in order to connect several sensing optical fibers (each of them incorporating several tens of wavelength-multiplexed FBG transducers) whereas two internal channels were used for referencing (absolute wavelength referencing using a gas cell, and output optical power referencing). Such a system has been deployed for field tests during a European project – called CATIEMON – that will be described in details in the forthcoming sections.

Study case: the railway industry

The railway network deregulation policy has been in progress for several years in Europe and will soon become effective. So, in this context, the interaction between the Overhead Contact Line (OCL) and the pantographs becomes the new separating interface between infrastructure managers and train operators, standing and rolling stock. Therefore, the monitoring of this interface becomes relevant for a better availability of the interoperated networks. It will contribute to a decrease of the traffic interruption and of the maintenance costs [1].

At the former IWSHM conference in Stanford (2007), we presented the 5th European Framework Program (FP5) SMITS project (*Smart Monitoring of Train Systems*) devoted to the contact force measurements between a train pantograph and its OCL [2]. SMITS project guideline was to give the rolling stock operators an on-board tool to optimize in real-time the contact force parameters during daily operation to prevent pantograph excessive wear on the OCL (to comply with standing stock specifications) and predict more accurately current collectors carbon strips lifetime to proceed to predictive maintenance. To do so, several well-suited electromagnetic-immune optical Fibre Bragg Grating (FBG) sensor lines were embedded by SMITS partners into the pantograph current collectors, turning them into two 3 points bending-based sensors in contact with the OCL.

6000 km on-line validation tests were performed during one week on a very high speed double-deck train "TGV Duplex" between Paris and Vendôme (France) at speeds up to 320 km/h. Contact forces between the pantograph and the OCL, as well as temperatures inside the current collectors, were computed and successfully compared in real time (500 Hz on 4 lines in parallel) with the existing traditional electrical gages provided by the SNCF for reference measurements. During these TGV tests, the innovative FBG measurement system developed by the CEA LIST has demonstrated its reliability and accuracy with temperature measurements, and coherence with contact force measurements in comparison with SNCF reference records.

Thanks to these good results, a second European project driven by Siemens (D)[1], acronym CATIEMON *(CATenary InterfacE MONitoring)*, started in 2005, supported by the 6th European Framework Program (FP6) [3]. The motivations for such a new project are as follows: monitor and investigate the pantograph/catenary interactions directly "from the wire", measure the contact force applied by a pantograph to the OCL, minimize the infrastructure maintenance costs, prevent catenary-pantograph incidents and thus traffic interruptions, propose solutions for an automated alert system. Monitoring operations of the overhead infrastructure are regularly planned, and executed by railways companies with dedicated trains. But, such operations are complicated to realize, and imply expensive equipments as well as high-skilled people. Moreover, these methods of surveillance are only able to determine defects linked to the infrastructure, and not problems associated to trains.

In fact, badly adjusted pantographs and/or damaged current collectors may also be a source of incidents. Indeed, a too strong contact force induces an excessive wear on the OCL and cause damages to the infrastructure. On the contrary, a too weak contact force will generate electric arcing when loosing contact - damaging the pantograph carbon strips as well as the OCL - but will also induce fluctuations of electrical current, limiting train speed.

So, to anticipate potential problems caused to both the infrastructure and the pantographs, a concept of inspection gate has been designed and developed by the consortium [7]. Positioned permanently and in a strategic point of a railway grid, it includes various types of sensors, and their associated instrumentations, enabling local (*i.e.* in well-known conditions) characterization and diagnostics at the OCL-pantograph interactions [4, 5]. Such a control gate aims not only at stopping a train presenting an immediate risk for the infrastructure (and thus reduce the risks of incident, as in tunnels) but also at estimating the impact of any train in term of infrastructure wear. In the CATIEMON project, the CEA List has been developing several FBG-based sensors 1) Uplift sensor based on displacement FBG sensors, 2) FBG-Impact sensors, and 3) distributed strain measurement of OCL with several FBG chains glued on the copper wire) and of course FBG demultiplexing units.

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

Railway control gate specifications

The control gate developed within the framework of the CATIEMON project is a first prototype. So it includes various measurement technologies developed by the partners: rangefinder laser for 1D uplift measurement, laser scanner coupled with a camera for a two-dimensional uplift measurement (vertical and horizontal), 3D FBG-based displacement sensors, and distributed FBG strain sensors.

Nevertheless, FBG-based metrology was the only technology capable of performing the complete range of the measurements, namely the 3D uplift (FBG triangulation sensor) of the OCL, and the distribution of strain along the contact wire. A steady arm (anchor arm used to define the contact wire position with respect to rails) was also instrumented with FBGs for hit detection. Figure 1 illustrates the location of these FBG sensors on the inspection gate.

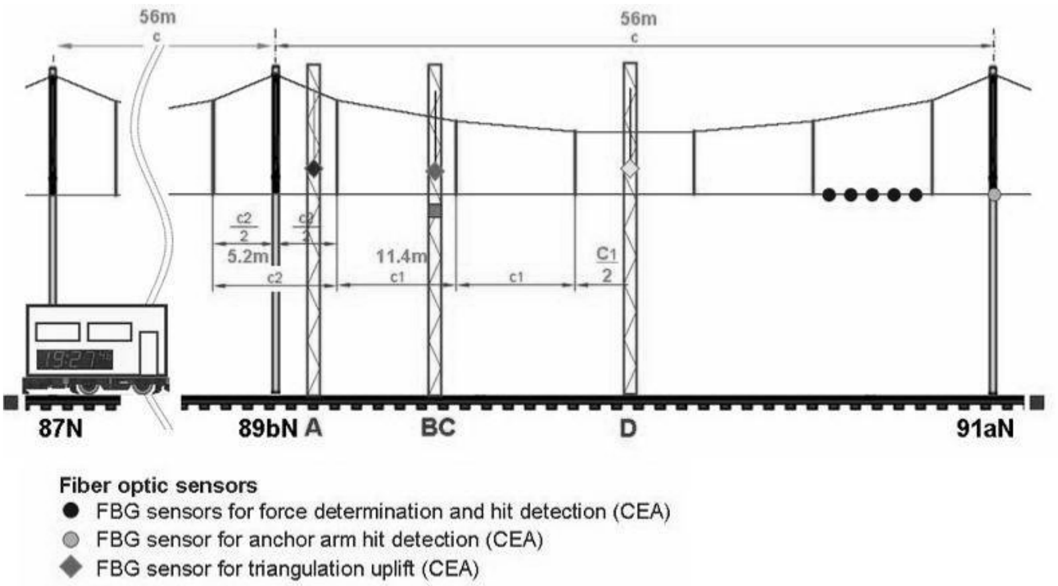

Figure 1. Control gate installed in Switzerland (Lötschberg), including several FBG sensors and remote FBG measurement systems.

TECHNICAL DEVELOPMENTS

Fiber Bragg Gratings (FBGs) are well known diffraction gratings photo written by UV laser interferometry within the core of singlemode fibers. An FBG consists of a submicronic modulation of the fiber core refractive index ‘n’, and acts as a reflector for a very narrow spectral bandwidth centred on a characteristic wavelength ‘λ_B’ that is directly dependent on its pitch ‘Λ’, through the well known relation $\lambda_B = 2.n.\Lambda$. The Bragg wavelength depends on both temperature and strain (Fig.2).

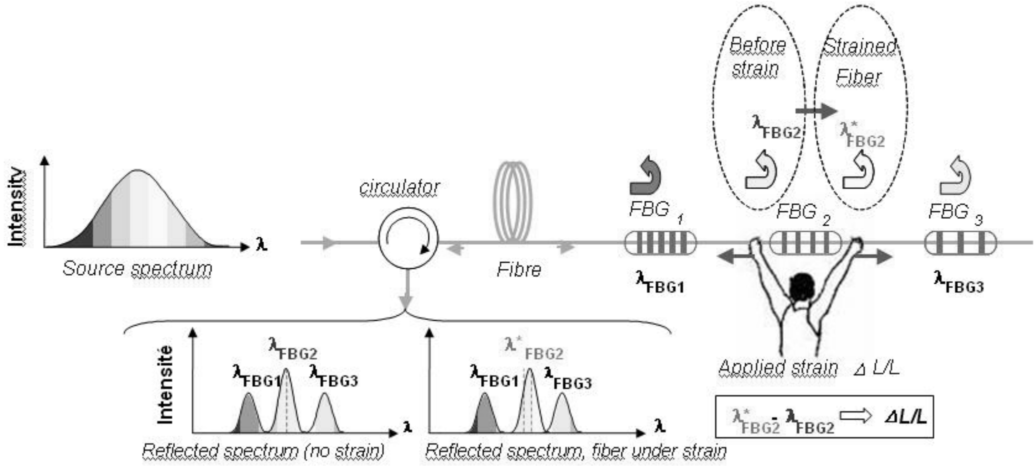

Figure 2. FBG principle: the spectral effect of strain on Bragg wavelength.

BraggFit[3] demultiplexing system

The *BraggFit*[3] system is made up of an industrial rack and a PC with a dedicated software. It enables accurate static and dynamic measurement up to the kHz, and its absolute wavelength referencing procedure.

***Bragg Fit*[3]** performances are listed below.

Measurement performances	Measurement range: 30 nm (1.55 µm range, C band)
	Resolution: better than 1 pm at 1 kHz / 0.1 pm at 10 Hz
	Stability: over 24 h / over 20°C < 1 pm
	Gain 40 dB (adjustable for each channel)
	Frequency scan: 1 kHz (6 channels of 30 nm swept in 1 ms)
Measurement channels analysed in real time	Number of simultaneous channels: 6 fibers (up to 10 in option)
	Number of sensors per channels: 30 typ. *(Depending on the spectral bandwidth allocated to each FBG-based sensor)*
	Optical connectors : E2000/APC (other in option)
Processing	Data logger: Autonomous system, Data acquisition / storage Client / server operations
	Client software: Display / Processing / Parameter set-up
	Data format: Binary file
	Interfaces: Ethernet / WiFi
Electrical characteristics	Voltage: 100-240 V; 50-60 Hz
	Power: 220 W
Others	Dimensions: 3U / 19’’ - Weight: 10 kg

Obviously, this *BraggFit*[3] system (Fig. 3) developed during the CATIEMON project is designed for interrogating all types of FBG optical fibre sensors (temperature, strain, pressure, force…). It is so powerful that it meets the needs of different application fields devoted to Structure Monitoring and the development/monitoring of Smart Manufacturing composite material for instance.

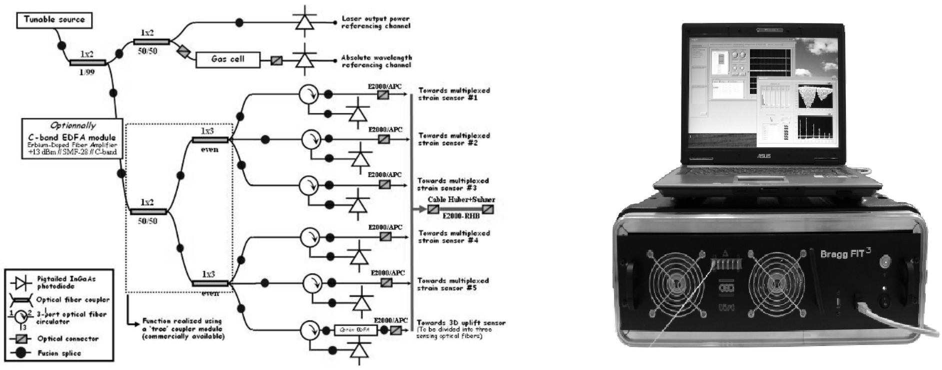

Figure 3. BraggFit³ monitoring system architecture and picture.

BraggLight measurement system

The *BraggLight* system realizes the FBGs 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 connection. With this basic design (Fig. 4) only one fiber is connected, but multi-channel versions are also possible.

Figure 4. *BraggLight* monitoring system.

BraggLight performances are listed below.

Measurement performances	Measurement range: up to 80 nm (1.55 µm range)
	Resolution: 0.5 pm
	Accuracy/repeatability: 5 pm
	Thermal stability: 1 to 2 pm/°C (compensation available)
	Frequency scan: 200 Hz
Measurement channels analysed in real time	Number of simultaneous channel: 1
	Number of sensors per channels: Typ. 30 *(Depending on the spectral bandwidth allocated to each sensor FBG-based sensor)*
	Optical connector : E2000/APC (other in option)
Processing	PC / software: Power supply, Driving / Parameter set-up, Data acquisition / Storage, Display / Processing
	Data format: Text file
	Interface: USB
Electrical characteristics	From USB link
	Consumption < 500 mA
Others	Dimensions: 165 x 173 x 56 mm^3 - Weight: 1 kg

4. FIELD TESTS

FBG line installation on High Voltage OCL with the *BraggLight* system

Both sensors and measurement systems were installed on a site located in Switzerland, upstream to a tunnel drilled under the Alps and open in 2007 (the Lötschberg tunnel), *i.e.* a very critical location. To avoid perturbing the commercial traffic, the work was done at night (less traffic).

The working conditions (at night, bad cold weather, wind) required specific installation procedures, especially for the FBG line gluing on contact wire (Fig. 5).

These sensing lines were fixed with special UV epoxy glue, using a UV lamp equipped with a fiber bundle. With such equipment, epoxy curing was performed relatively quickly, and continuously, while at the same time repetitive FBG spectra were acquired to control the curing process.

To perform this outdoor optical control, a dedicated FBG measurement system, small, portable and autonomous, has been developed. The *BraggLight* system monitors, in real time, the curing process in case of lack of power supply (it just needs an USB link to the PC for both power supply and data transfer).

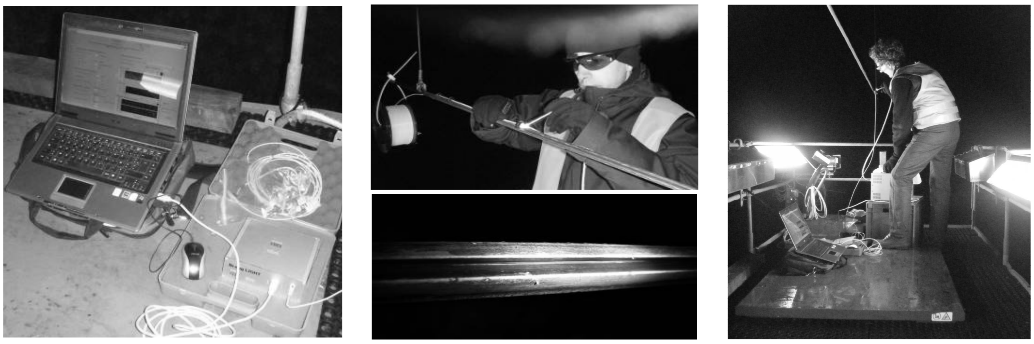

Figure 5. *BraggLight* unit used for real-time control of FBG line epoxy curing on contact wire.

Traffic monitoring with FBG sensors and high performance *BraggFit*^{3} system

A BLS locomotive was used to calibrate the sensors *versus* applied contact force (50 N, 70 N, 90 N) and train speed (from 40 km/h to 100 km/h, maximal authorized speed at the gate location). The main objective was to investigate the possibility to link these two parameters with the measurements given by the optical fibre sensors (displacement, strains).

Calibrations were performed at night, and during several field tests spreading out over 18 months. During the same periods, we also collected the sensor data while the Inspection Gate was crossed by commercial trains (passengers and freights). This gave the strain distribution along a section of the OCL during the train transit along the Inspection Gate.

To do it, we simply detect the spectral Bragg lines due to local strain associated with every pantograph carbon strip(s) of a considered train. Then, we average the Bragg wavelength associated to the distributed FBG-line. With these reference data, it’s now possible to identify a train out of ‘standard’ distribution, and potentially harmful to the infrastructure.

Figure 6. FBG measurement units in the container to control any train passing the control gate.

CONCLUSION

Several electromagnetic-immune optical FBG-based sensors and two powerful measurement units have been developed by the CEA List to equip the Inspection Gate. The picometric resolution *BraggLight* instrument is a small form factor unit able to scan at 200 Hz an 80 nm spectral band, *i.e.* some tens of FBG sensors. Just needing an USB link, this handable system provides its full potential in outdoor measurements, or where power line supply is not available. The second instrument, the *BraggFit*[3] system is characterized by a very high level of performances: up to 10 optical fibers spectrally scanned in real time at 1 kHz, with resolutions better than 1 pm (# 1 µm/m or # 0.01°C) , enabling to interrogate several hundreds of FBGs.

These powerful systems look like really 'universal', enabling to interrogate any FBG sensor photo-written in the 1.55 µm spectral range, and coming from any company. This may provide useful and powerful solutions in several industrial sectors (transportation, marine, aeronautics, civil engineering …), for structure monitoring & smart structure purposes.

Concerning railway industry, these new instrumentations enable to control the rolling stock operators' compliance with the infrastructure rules, and eventually to stop harmful trains identified by the control gate.

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