High speed real-time contact measurements between a smart train pantograph with embedded Fibre Bragg Grating sensors and its Overhead Contact Line

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ABSTRACT

Enhancing train transportation is a key issue as competing transportation means are gradually becoming saturated in capacity. The European Union (EU) tries to promote this by developing initiatives and enhancing the competitiveness of the rail grid by means of deregulation and interoperability, supporting this process with a planned upgrade to the existing rail network.

The SMITS project (Smart Monitoring of Train Systems) of 5th European Framework Program (FP5) has been specifically devoted to control the contact force between the train pantograph and the Overhead Contact Line (OCL), enabling both the infrastructure managers to control the rolling stock operators compliance with their infrastructure rules (*e.g.*: pantograph maximum wear on the OCL), and the rolling stock operators to optimize the wear conditions and proceed to predictive maintenance.

In such a context, several well-suited electromagnetic immune Optical Fibre Bragg Grating (FBG) sensor lines were integrated by SMITS partners into the current collectors, turning the pantograph into a 3 points bending-based sensor in direct contact with the OCL, offering the advantage to be less sensitive to inertial forces (especially those introduced by pantograph suspending devices), which should lead to more accurate measurements.

A semi-empirical model, validated by FEM analysis and several laboratory tests performed at high voltages, was introduced into the signal processing software of a dedicated highly accurate and auto-calibrated FBG measurement system (accuracy and drift lower than 0.6 pm @ 1550 nm, and at 500 Hz measuring rate), providing simultaneous measurements over several FBG optical lines.

On-line validation tests were performed during a full week on a very high speed train “TGV Duplex” between Paris and Vendôme (France) at speeds up to 320 km/h, leading to equivalent linear resolution better than 20 cm along the track.

Contact forces between the pantograph and the OCL, as well as temperatures inside the current collectors were computed in real time at 500 Hz, on 4 lines in parallel, and immediately transmitted to the SNCF reference measurement system for comparison and validation.

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.

INTRODUCTION

The train network deregulation policy is in process in Europe. In this frame, the interaction between the Overhead Contact Line (OCL) and the current collector on the pantograph becomes a new separating interface between independent track and train operators, standing and rolling stock: therefore, the monitoring of this interface appears to be relevant for a better interoperability between foreign companies whose average rates of failures, close to 4-5 events/100 km a year, can potentially cause the traffic to be blocked [1].

In this frame, the European SMITS (Smart Monitoring in Train Systems) consortium, involving several European actors such as train operators, industrial companies and R&D laboratories [2], had for objective to satisfy these new needs for diagnostics both on rolling stocks and electrical infrastructure, by developing and qualifying a complete new solution to monitor thermal and mechanical stresses caused on the OCL by a running train, including:

- a high-speed and accurate measurement system capable of real-time measurements and compatible with existing rolling stock equipments,
- a smart current collector with embedded sensors compatible with high-voltages and aero dynamical constraints,
- numerical models to predict the contact temperatures and forces between the pantograph and the OCL, allowing the wear to be predicted.

STATE OF THE ART – TRADITIONAL SOLUTIONS WEAKNESSES AND SMITS SOLUTION

Until now, traditional contact force measurement techniques between the OCL and the current collector consist in using calibrated strain gages inside the pantograph suspensions [3, 4]. These techniques are proven to be simple from the mechanical point of view, since they consist in force and force momentum equilibriums.

However, these techniques have to face intrinsic difficulties due to:

- the high voltages (up to 25 kV on the OCL), which requires galvanic insulation for both accurate measurements and human safety,
- the pantograph stiffness, which usually leads to low strain levels,
- the distance between the sensors and the OCL contact point, which makes inertial forces compensation very difficult for any component in between.

On the contrary, SMITS strategy consists in using embedded Fibre Bragg Grating sensors in the current collector, as close as possible to the OCL contact point, leading to several advantages:

- the location of the OCL contact point and the sensors in the same vicinity, turning the current collector into a “smart sensorised” current collector, potentially capable of temperature and vertical forces measurements with a 3 points bending based model leading to more accurate measurements since inertial compensations are reduced to their minimum,
- the FBG sensors electromagnetic immunity used as strain and temperature gauges, without any impact of surrounding high voltages on measurements.

However, some difficulties remain from the measurement point of view:

- the strains are often lower than 100 µm/m, mainly due to the current collector stiffness, which necessitates spectral resolution and accuracy better than 0.6 pm to reach 1 N vertical force resolution,
- the very high speeds reached by the TGV (up to 320 km/h on commercial lines) requires high measurement rates (500 Hz) to detect close OCL flaws,
- the numerous parallel FBG optical lines require a measurement system capable of measuring simultaneously their Bragg wavelengths.

The main role of the CEA LIST in the SMITS project was:

- to develop a new FBG monitoring system capable of real-time accurate and simultaneous wavelength measurements over several optical lines,
- to integrate this monitoring system into the SNCF measurement loop for on-line qualification tests at very high speeds on SNCF TGV Duplex train between Paris and Vendôme for real-time comparisons of vertical contact force and temperature measurements, traditionally performed with electrical strain gages and thermocouples.

Since the CEA LIST tasks were mainly focused on both the monitoring system development and the qualification tests, this paper deals mainly with these two topics; the sensors aspects, mechanical modeling and industrial process are mentioned necessary and for illustration purposes.

OPTICAL LINES TOPOLOGY AND MEASUREMENT SYSTEM

Current collector sensors topology

As described above, the measurement principle relies on a 3 points bending model: the current collector is equipped with several Fiber Bragg Grating Sensors located at different positions in order to be sensitive to both vertical and horizontal forces (fig. 1):

- 2 strain and temperature sensors in the middle of the current collector,
- 2 strain and temperature sensors on each side of the current collector,

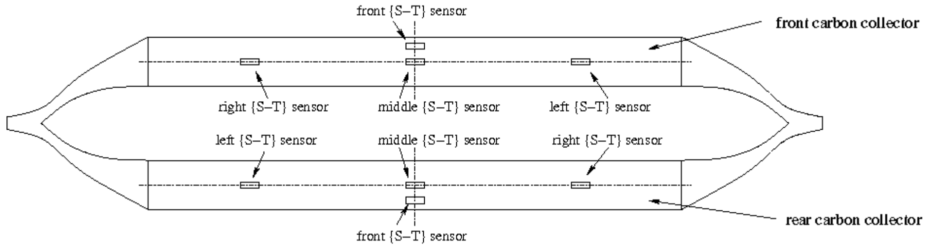

Figure 1. Embedded sensors position into the current collector (CX25 pantohead – bottom view).

turning the current collector into a force and temperature sensor since FBGs are sensitive to both strains and temperature according to the well-known relationship:

$$\frac{\Delta\lambda_B}{\lambda_B} = a\,\frac{\Delta T}{T} + b\,\Delta\varepsilon + c\,\frac{\Delta P}{P} \quad \text{with} \quad \begin{cases} a \approx 2.3\times10^{-3} \\ b \approx 0.78 \qquad (free\ fiber) \\ c \approx -2.94\times10^{-6} \end{cases} \qquad (1)$$

where λ_B is the Bragg wavelength, ε is the strain, T is the temperature and P is the hydrostatic pressure (constants a, b and c given here for a free fiber). It appears that in most common applications, the sensitivity to hydrostatic pressure can be neglected; therefore, only 2 sensors are necessary to extract the strain ε and the temperature T; in our application, *S*-type sensors are sensitive to both strains ε and temperature T, whereas *T*-type sensors are only sensitive to temperature [5, 6, 7].

Measurement safety purpose in case of fiber break – Consequence on the measurement system bandwidth

To guarantee the measurements reliability, each current collector was equipped with 2 optical fibers, each one with 2 strain and temperature {S-T} sensors. This specific redundant topology leads to 4 optical lines scanned in parallel for wavelength detection, which doubles the bandwidth required for the measurement system.

TEMPERATURE AND VERTICAL FORCE MEASUREMENT PRINCIPLE

As described above, the measurement principle relies on 3 points bending: the current collector is equipped with several Fiber Bragg Grating Sensors located at different positions in order to be sensitive to vertical contact forces, and in a lesser extent, to horizontal contact forces too, since there are 2 sensors located in the middle of the current collector (fig. 1).

Modeling

Vertical contact force F, contact position x and temperature T are computed from wavelengths shifts according to semi-empirical models with calibration constants (model provided by IPHT):

- the temperature T behaves linearly with the wavelength λ according to:

$$T(\lambda) = m \cdot \lambda + b \qquad (m \text{ and } b \text{ constants}) \qquad (2)$$

- the vertical contact force F is computed from a 3 points bending problem, depending on the position of the contact point (on the right or on the left):

$$\begin{cases} F = \dfrac{\varepsilon_{right} - \varepsilon_{middle} \cdot \left(\dfrac{2 \cdot xn}{L} - 1 \right)}{\dfrac{L^2}{2} - xn \cdot L} \cdot \dfrac{1}{C1} \\ F = \dfrac{\varepsilon_{left} - \varepsilon_{middle} \cdot \left(\dfrac{2 \cdot xn}{L} - 1 \right)}{\dfrac{L^2}{2} - xn \cdot L} \cdot \dfrac{1}{C1} \end{cases} \quad (C1, xn, \text{ and } L \text{ constants}) \quad (3)$$

- the contact position x is computed according to the same principle:

$$x = C \cdot xn \cdot \frac{K \cdot \varepsilon_{right} - \varepsilon_{left}}{K \cdot \varepsilon_{right} + \varepsilon_{left}} \quad (C, xn \text{ and } K \text{ constants}) \quad (4)$$

The calibration experiments

Calibration constants are obtained with laboratory tests:

- the current collectors are first placed into a climatic chamber: Bragg wavelength shifts are recorded for different temperatures; regression analysis give the calibration constants *m* and *b* for each current collector,
- then, the current collectors are assembled on the pantohead, and several calibrated weights are placed at different positions on it; regression analysis give the remaining calibration constants *C*, *K*, *C1*, *xn*, and *L*.

Calibration control procedure

Once the calibration constants computed, the model is tested in laboratory: it consists in placing several weights at different positions on the pantohead and controlling that the computed weights and position parameters are in agreement with the experiment. Similar tests are performed with the pantohead in contact with its OCL at 25 kV voltages.

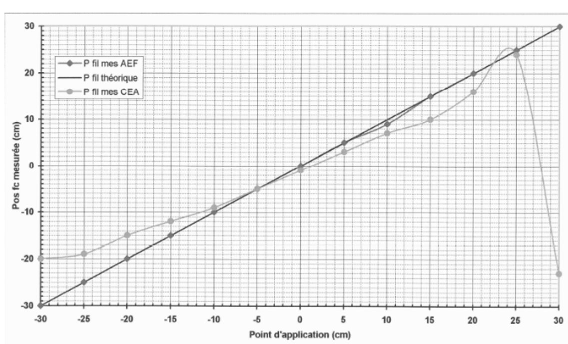

Figure 2. Sensors position calibration control procedure: computed position *vs.* real position.

It appears that the model fits pretty well the reality, except when the contact points are outside the left and right sensors, mainly due to a model limitation (fig. 2).

OPTICAL MEASUREMENT SYSTEM BASICS

In order to fit the specifications required by very high speeds conditions (up to 320 km/h, and 350 km/h on recent European eastern TGV line), the end-users required to be able:

- to see flaws with a linear resolution close to 20 cm, leading to 500 Hz measurement rate,
- to detect 1 N vertical force variations, leading to equivalent 0.6 pm spectral resolution,
- to get the physical data (force, position and temperature) in real-time as available analog outputs in order to be recorded and compared during the on-line trials between Paris and Vendôme for the TGV tests.

Inside the measurement system: a high speed tunable laser source

These requirements lead our R&D laboratory to develop a specific optoelectronic system based on a high signal-to-noise tunable laser whose emission is based on cascaded filtering, and scanning frequency controlled by a PZT actuator [8, 9, 10].

Wavelength calibration is performed thanks to an embedded wavelength reference device which ensures accurate absolute wavelength measurements: accuracy, precision and drifts are controlled – peak to peak – to be smaller than 0.6 pm at 500 Hz (fig. 3).

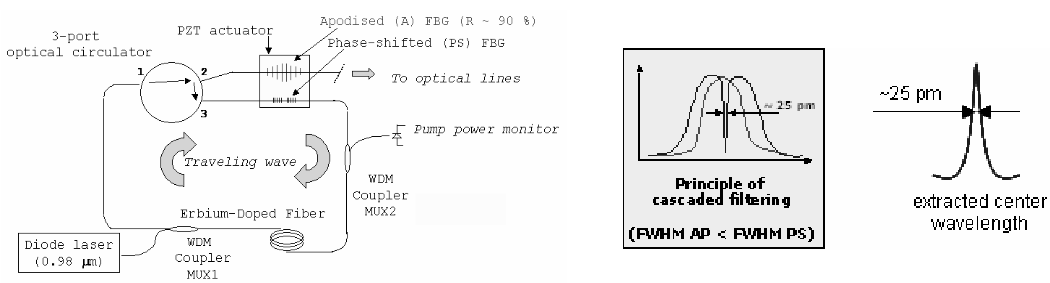

Figure 3. High scanning frequency tunable laser principle from CEA LIST.

TGV FIELD TESTS BETWEEN PARIS AND VENDÔME

The on-line qualification trials during a full week in March 2005, between Paris and Vendôme, consisted in measurements comparisons between the SNCF traditional strain gauges and FBGs measurements: both SNCF and CEA systems were coupled in order to deliver real-time status.

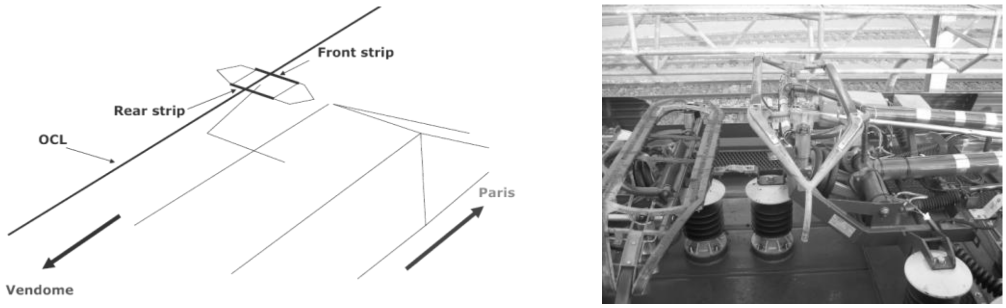

Figure 4. Pantograph configuration for Paris-Vendôme TGV field tests.

Master wavelength server and supervision client measurement system

The measurement system optoelectronics has been embedded into an industrial 19" rack with specific software in order to deliver in real time the physical parameters requested by the end-users.

This optoelectronic part behaves like a black box and acts as a "master wavelength server" which sends its data over an Ethernet link to a "supervision client" which computes, from these wavelengths, the force, position and temperature parameters, and displays them on graphics in real-time. Moreover, the "supervision client" generates several 0-10 V analog outputs for SNCF reference system records (fig. 5).

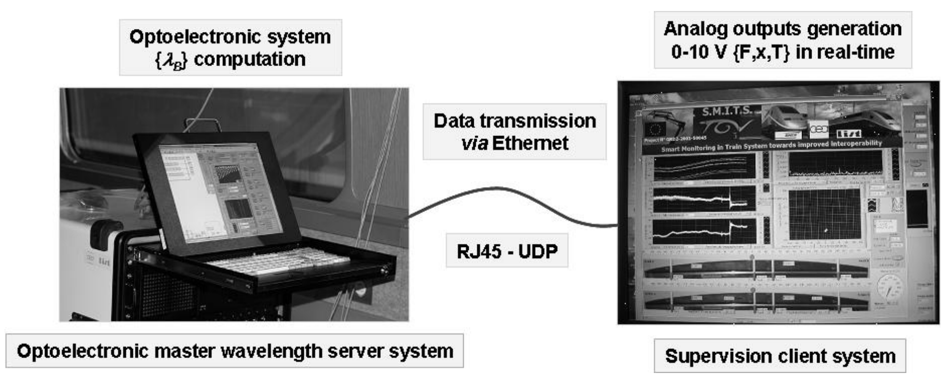

Figure 5. "Optoelectronic master" and "supervision client" monitoring system configuration.

TGV field tests

During more than 6000 km, field tests measurements were performed and several significant results were obtained (fig. 6):

- temperature inside the current collector gave better results than expected: temperature gradients in the pantohead were observed up to 160°C/m,
- contact point position was observable, and its zigzag movement was compatible with the distance between two consecutive pylons,
- vertical contact force was also measured, but required on-line temperature compensation due to temperature gradients influences.

And last but not least: our optical measurement system did not fail during the tests.

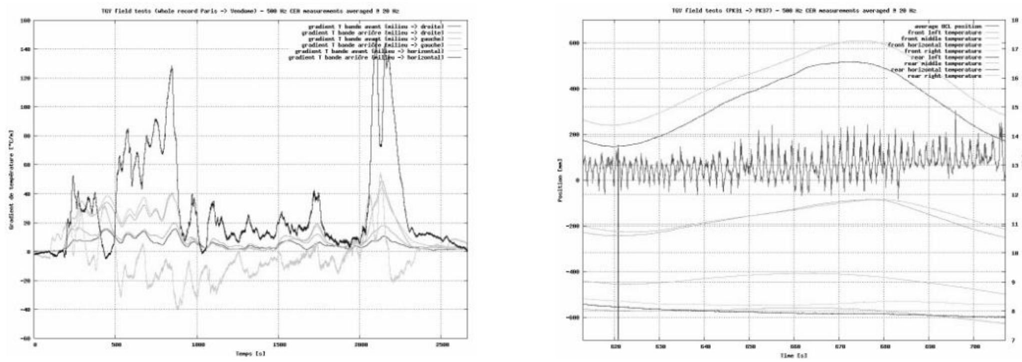

Figure 6. Temperature gradients (left) and OCL contact point position on the pantograph (right).

CONCLUSION

FBG sensors and related measurement systems have demonstrated their ability to be used in harsh environments (high voltages, very high speeds) for real-time measurements as encountered in railway industry. Today, like SMITS, more and more projects require higher scanning rates, better resolutions, and simultaneous measurements on a higher number of optical lines: the CEA LIST was able to build such a system compliant to project specifications, and now continues these developments in the EU funded CATIEMON project for enhanced performances.

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