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A temperature compensated fibre Bragg grating (FBG)-based sensor system for condition monitoring of electrified railway pantograph

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ABSTRACT

This paper presents the results obtained from fibre Bragg grating (FBG) sensors integrated into a railway current-collecting pantograph for accurate measurement of contact force and contact location when it is subjected to various temperature conditions. The temperature change of the pantograph is simulated, at the industrial laboratory of Brecknell Willis in the UK, by changing the DC current applied to pantograph from 0 to 1500 A. This test is primarily designed to verify the effectiveness of the temperature compensation mechanism built in the FBG sensor design. For this verification, 3 thermocouples co-located with the FBG sensor packages are used to measure the temperature change seen from 25 ºC to 55 ºC. The tests were repeated several times and the sensor system has shown its temperature-independence, confirming that the intrinsic cross-sensitivity of FBGs to temperature variation for strain measurement has been fully compensated through the use of this innovative sensor design and data processing.

Keywords: Fibre Bragg Grating (FBG) Sensors, railway pantograph, condition monitoring, electrified pantograph

1. INTRODUCTION

Fibre Bragg grating based optical sensors have become an important sensing element for the measurement of strain, temperature, and a wide range of other parameters in a number of industrial applications[1]. Their immunity to electromagnetic interference, ease of multiplexing, small size and lightweight have made them well-suited for measurement in various harsh and extreme conditions[2]. One typical example, as detailed in this paper, is to integrate FBGs into a railway current-collecting pantograph for remote condition monitoring as it is exposed to all weathers and powered at 25,000 volts when an electric train is in operation at high speeds up to 350 km/h. Using optical fibre sensing technique has shown its unique advantages over its electrical counterparts due to its immunity to electromagnetic interference.

In addition to the FBG-based sensor systems, optical fibre-based interferometric systems have been reported by Boffi et al, for example, using a Mach-Zhender fiber interferometer to achieve a distributed force measurement[3] of a pantograph and then by a 3x3coupler to configure a Michleson's interferometer[4] for measurement.

The major drawback of using a FBG-based technique is its cross-sensitivity to strain and to temperature, therefore a significant amount of effort has been made to compensate the temperature effect when a FBG is used for strain measurement. Camolli et al[5] reported the use of two single FBG sensors on separate fibers, where one of the FBGs is used for temperature compensation. This approach is based on the assumption that the temperature distribution is uniform along the pantograph, however this is not necessarily the case in a real time situation. The other FBG-based sensor system[6] deploys the use of aluminum boxes confining 3 FBG sensors within a small footprint, with one strain-free FBG for temperature compensation. Each pan-head is instrumented with two boxes which increases the mass and consequently affects aerodynamic force when the train moves at high speeds. Embedding the FBG sensors between carbon and aluminum has been reported by Schroder et al[7]. All the reported FBG techniques require either an additional fibre or an additional FBG for temperature compensation. Considering the high temperature sensitivity, which is one order of magnitude higher than that of its strain sensitivity, it is challenging to remove the temperature effect in a satisfactory way and this forms the core of this research.

Updated 3/20/14

2. FBG-BASED PANTOGRAPH CONDITION MONITORING SYSTEM

An FBG is a piece of an optical fibre with periodically modulated core refractive index in such a way it creates a narrow band reflection. The principle of operation of an FBG-based sensor system is based on monitoring of the wavelength shift of the reflected Bragg signal, as a function of a measurand, such as strain or temperature applied to the FBG. The reflected wavelength is called the Bragg wavelength (λ_B) and it is related to the effective index of refraction of the fibre core (n_{eff}), and the grating pitch (Λ) by the following equation[1]:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Figure 1 shows a schematic diagram of an FBG array, comprising 9 FBGs, being integrated into a pantograph with the sensor data being captured using an interrogator prior to data processing using an appropriate algorithm built in the software developed.

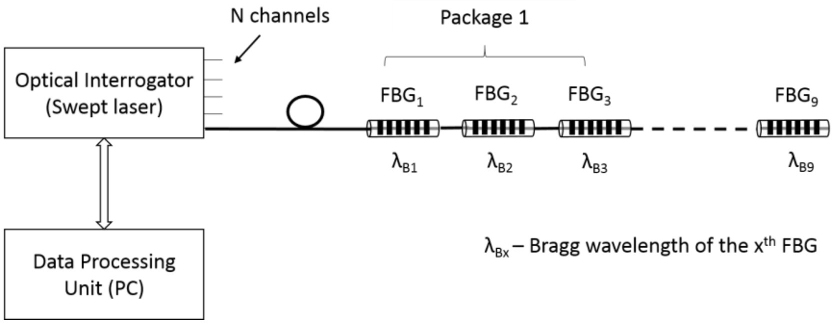


Figure 1. Demonstration of an instrumented pantograph integrated with an array of nine FBGs

This paper reports a novel temperature compensation method by using a package-based sensor design and as shown in Figure 2, three FBG-based sensor packages are integrated into three different locations of a pantograph, both for real-time measurement of the contact force and contact location and for temperature compensation. Given the small footprint of each package, it is observed that the FBGs in the same package experience the same scale of temperature variations. This effect has been exploited in this research for effective temperature compensation.

3. TEMPERATURE COMPENSATED CONTACT FORCE MEASUREMENT

To verify the above sensor design idea, Figure 2 shows an experimental setup created for the evaluation of the developed temperature compensation method for the contact force measurement under high current conditions. As shown in the figure, a current supply was connected to both sides of the pantograph, allowing for a step change of current from 0 to 1500 A and then from 1500 A to 0A to be applied. The higher current applied induces temperature change in the range from 25 ºC to 55 ºC over a period of 9 minutes, as recorded by three thermocouples, which were co-located with 3 FBG packages as shown in Figure 2. To speed up the cooling process, a fan is used. During the whole measurement process, there is no contact force applied to the pantograph.

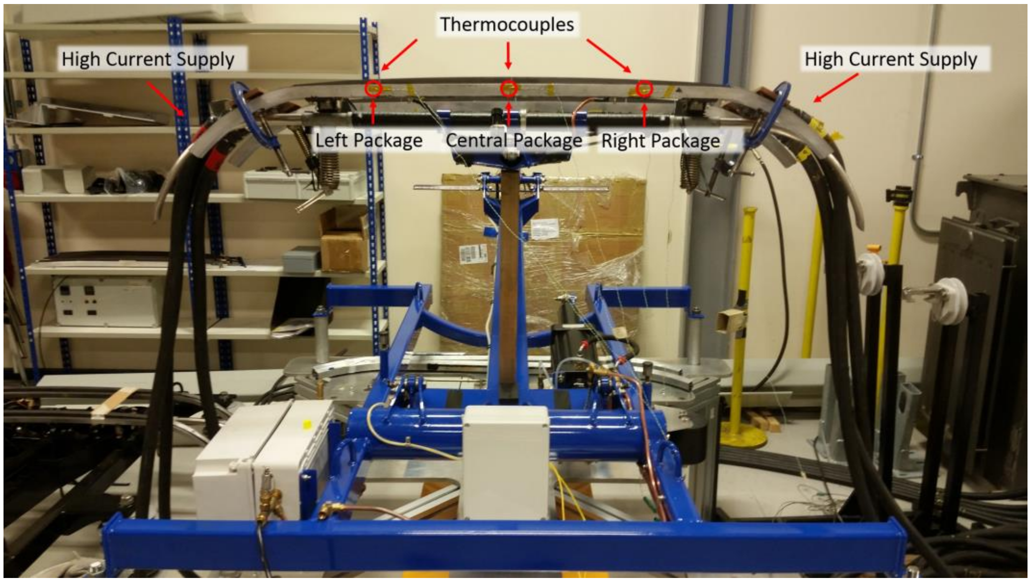


Figure 2. Pantograph driven by a DC current, changing from 0 to 1500A and then from 1500 to 0A, when the contact force is zero.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows the current applied and the temperature change recorded by the thermocouple which is co-located with the central FBG package. The current supply is switched off when 55 ºC is reached and a fan is used to accelerate the cooling process.

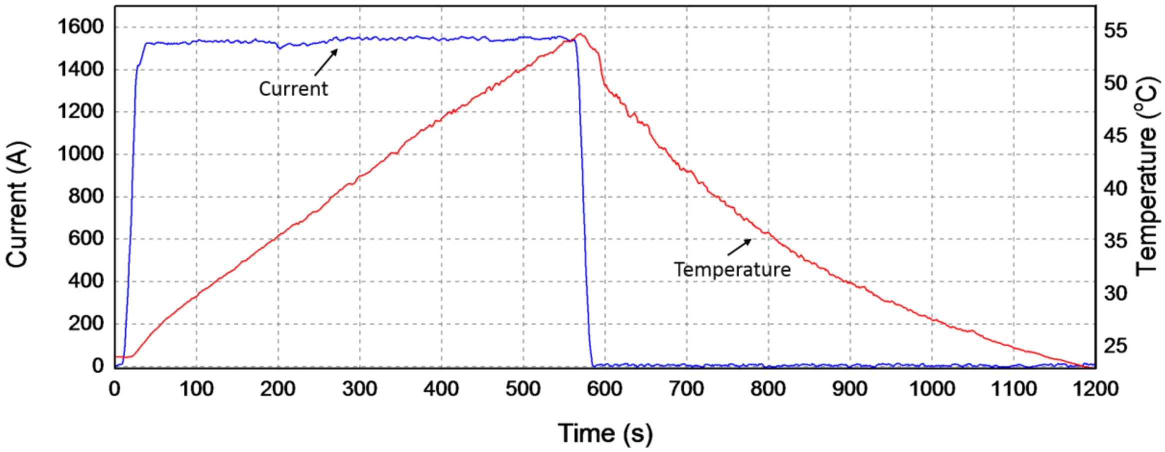
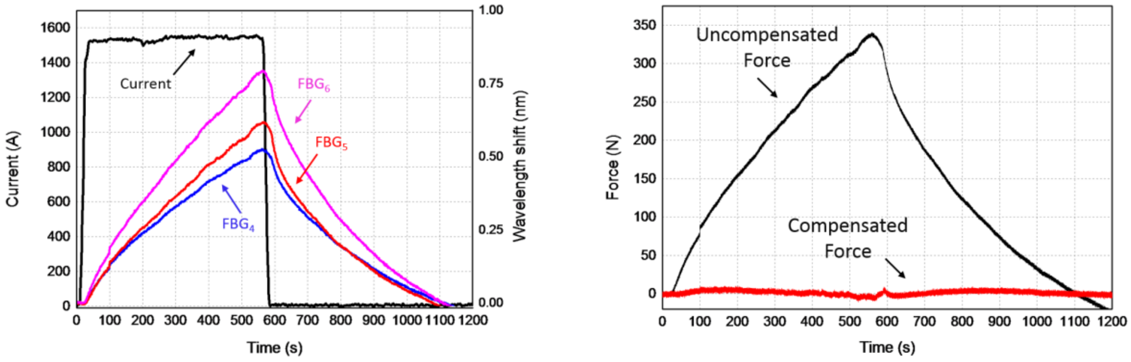


Figure 3. Temperature change recorded by the central thermocouple and current value applied to the pantograph during the experimental tests

Figure 4(a) shows the wavelength shifts of three FBGs, i.e. FBG_4, FBG_5 and FBG_6, confined in the central package and located at the central area of the pantograph when a step change of current is applied to the pantograph from 0 to 1500A and then from 1500 A to 0A. The wavelength shift of each FBG within the same package experiences the change in applied strain (from the contact force) and in temperature. The latter however can be subtracted based on the correlation of FBGs within the same package as a function of the temperature variation and this underpins the algorithm developed for temperature compensation at City University of London. The black curve in Figure 4 (b) shows the contact force calculated from the data recorded by the central FBG package without considering temperature compensation. The red curve in Figure 4 (b), however, shows clearly the contact force to be zero after the implementation of the temperature compensation algorithm developed and this agrees well with the test condition as the pantograph was electrified but without being in contact with the overhead line equipment (OLE). It is noticeable that temperature compensated FBG-sensor system removes the effect from the temperature changes and provides the information of the force being unaffected by the applied current.



a) b)

Figure 4. (a) Wavelength shifts of FBGs 4, 5, 6 in the Central package recorded during the experimental tests; (b) The contact force measured by FBG packages before and after temperature compensation.

Further to the above temperature-compensated contact force measurement using each FBG package, the contact location of the OLE against the pantograph can thus be obtained by calculating the ratio of the contact forces measured simultaneously by the three FBG packages integrated into the pantograph at three different, yet known locations.

5. CONCLUSIONS

This paper reports a novel sensor design through integration of FBG sensor packages into a railway current-collecting pantograph for its remote condition monitoring. This is designed to remove temperature effect in the strain/force measurement and under the circumstances that the temperature effect is more dominant. The positive outcomes obtained from the field tests, by driving the pantograph using high currents, have further confirmed the effectiveness of this method used for temperature compensation. The research is still on-going and more vehicle tests will be undertaken in the near future to evaluate extensively the smart pantograph developed in industrial settings.

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