Characterization on the distributed fibre optic sensors using a newly developed calibration system

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ABSTRACT : This paper presents the characterization of four tight-buffered strain cables and one loose-buffered temperature cable for the distributed fibre optic sensing using a multi-function calibration platform developed in the laboratory. The calibration platform comprises of two units: 1) an aluminum rig, which can automatically change the tested cable strain condition with the resolution of $1\mu m$ and the accuracy of $10\mu\varepsilon$; and 2) a water bath, which can uniformly change the embedded cable's temperature from 0-100°C with the resolution of $\pm$0.1°C and the accuracy of $\pm$0.05°C. Parameters that were tested to quantify the cable qualities are: the measurement accuracy, the measurement hysteresis during loading and unloading process, and the measurement's linearity of the measured Brillouin scattered frequency shift with regard to the input strain/temperature change. The quality of the five tested cables varied significantly and the sensing hysteresis was observed for several cables (e.g. temperature cable), which has to be considered in the future data analysis process when utilizing those sensing cables in the real site monitoring.

1 INTRODUCTION

Infrastructure monitoring is a very demanding application of the distributed fibre optic sensor (DFOS) in terms of distributed strain and temperature measurements. A typical DFOS system comprises two parts: the sensing cable and the analyser. When the analyser launches a light into the sensing cable, the majority of the light travels through the cable, but a small fraction is backscattered. By analysing the property of the backscattered light, cable's strain and temperature information can be obtained.

The key performance characteristics of DFOS could vary significantly using fibres with different cable tight buffering methods. There has been a number of calibration units reported in the past few years to evaluate the sensor performance. For example, a robust strain calibration device was developed in Zurich to calibrate the strain sensing cable parameters including cable longitudinal stiffness, yield strain, Brillouin conversional coefficient and fibre slippage(Iten 2011). A simple water tank was designed to compare the temperature coefficients for different types of sensing cables(Mohamad 2012) and a new 'dissimilar-fibre-splicing' method was proposed to calibrate sensor spatial resolution(Zhang, Cui, and Shi 2013). Most of the previous calibration experiment results verified that the sensing cable parameters can vary significantly for cables. It is therefore essential to calibrate the sensor and its measurement accuracy before applying it to the real site cases.

This paper presents the performance characteristics of five fibre cables commonly used in infrastructure monitoring, using a newly developed strain and temperature calibration platform. The strain calibration unit consists of an aluminium rig and a micro-meter mounted on it to automatically stretch the tested cable. The temperature calibration unit is a water bath which can accurately and precisely control the embedded cable's temperature. The cable performance was characterized in terms of the measurement accuracy, hysteresis and the linearity of the measured Brillouin scattered frequency shift with regard to the input strain/temperature change. Very different performance were found in the tested strain cables, due to varying bonding material and reinforcement used in the cable. The temperature cable shows some temperature hysteresis but that part of error is largely minimized after a few times heating and cooling cycles.

2 CALIBRATION UNITS

The distributed fibre optic sensor can be used to measure strain and temperate for infrastructure monitoring. To evaluate the performance of different sensing cables, a calibration platform was established in the laboratory. This platform is made of an aluminium rig for strain calibration and a water bath for temperature calibration.

2.1 *Sensing principle*

The basic principle behind the distributed fibre sensor is that ambient parameters such as strain and temperature can influence the properties of the light signal travelling throughout an optics fibre. Therefore, when light is launched into a sensing cable, the majority of the light travels through the cable, but a small fraction is backscattered and the frequency shift of the Brillouin backscattered light is proportional to the cable strain/temperature.

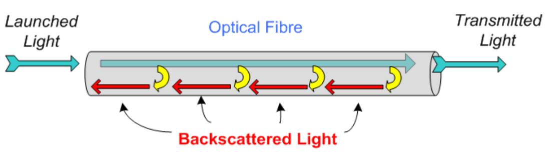


Figure 1. Brillouin backscattering on an optical fibre.

To convert the Brillouin frequency shift to strain/temperature measurement, coefficients (C_ε and C_T) are usually applied. However, for cables with different buffering methods, C_ε and C_T would be slightly different. For current available sensors, Brillouin C_ε vary in a range of 0.046-0.052MHz/$\mu\varepsilon$(Mohamad 2012).

Strain coefficient C_ε can be calculated as:

$$C_\varepsilon = \frac{v_B(\varepsilon) - v_B(\varepsilon_0)}{(\varepsilon - \varepsilon_0)}$$

Temperature coefficient C_T can be calculated as:

$$C_T = \frac{v_B(\varepsilon) - v_B(\varepsilon_0)}{(\varepsilon - \varepsilon_0)}$$

As has mentioned previously, the frequency shift of the backscattered Brillion spectrum is simultaneously sensitive to temperature and strain in the fibre. To distinguish them, strain sensing cable and temperature sensing cable are usually placed adjacent to each other for different measurements. The temperature cable consists of a loose buffered fibre to isolate strain effects and the strain cable contains a tight buffered fibre to efficiently transfer external strain to the fibre inside.

2.2 *Strain calibration platform*

The strain calibration set up (figure2) consists of an electrical motorized linear stage to change the cable strain precisely and accurately and an aluminium base structure to mount the micro-motor. The calibration bench was put in a temperature controlled room to minimize the temperature effect on the Brillouin frequency shift readings.

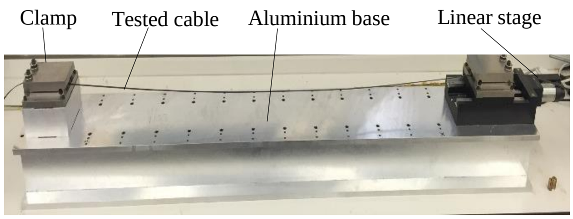


Figure 2. The strain calibration bench.

The micro-motor for cable stretching was selected as a M414 ball-screw type precision linear stage from PI Company considering its high performance in accurate motion control. Generally, this strain calibration bench can stretch 1.5m of the cable by a given displacement to a resolution of 1μm and to an accuracy of 10$\mu\varepsilon$.

Previous site strain measurement results showed that if the strain sensing cable's pre-strain is beyond 3000micron, the gel used to attach cable to structures will start to degrade and the pre-strain will start to reduce. Therefore the sensing cable for this strain calibration experiment was pre-strained by less than 3000$\mu\varepsilon$.

2.3 *Temperature calibration unit*

A water bath was used as temperature calibration bench to allow a certain length of the fibre optic cable to be thermally isolated from the remainder of the cable and maintained at a desired temperature. The temperature controlling system used in this test was a C1G cooling system and a T100-ST 18 water bath from Grant Instruments with the dimension of 200mm (h) × 540mm (l) × 330mm (w).

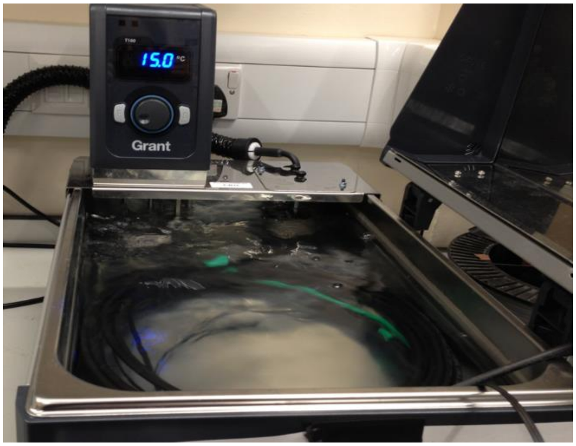


Figure 3. The temperature calibration bench.

This setup can uniformly change the cable's temperature from 0-100°C in a resolution of ±0.1°C with an accuracy of +/-0.05°C. The cable section was freely immerged into the water bath in the form of many loops as shown in Figure 3. There is a thermometer installed as well for temperature measurement reference.

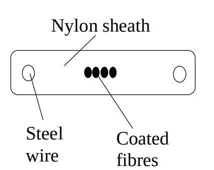
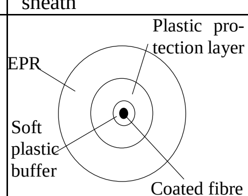
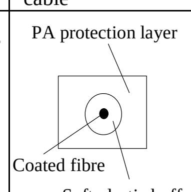
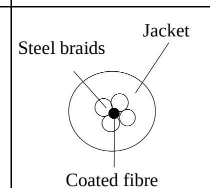
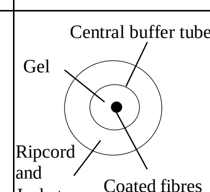
3 RESULTS

The calibration process generally contains: 1) holding a certain section of the cable, 2) changing its strain/temperature condition accurately and precisely, 3) evaluating the input strain/temperature data recorded by strain sensor (or thermometer) with the frequency shift displayed on the analyser. Four types of strain sensing cable and one temperature sensing cable were tested in the laboratory. Cable's measurement hysteresis, accuracy and its linearity between input strain/temperature with regard to analyser measured strain/temperature were evaluated to quantify cable's sensing ability.

3.1 Tested cable

Table 1 lists four strain sensing cable and one temperature sensing cable that were tested in the laboratory. The Fujikura Ltd. Designed strain sensing cable has four single-mode optical fibres embedded in the middle of the cable and two steel wires on sides to reinforce the cable. The ribbon shape of the cable makes it easier to attach the cable to structures. The Brugg Strain Cable has one single mode fibre tightly-buffered in a round tube. The jacket of this cable is so robust that it needs no reinforcement. The tight buffer telecomm cable is not particularly designed for distributed fibre optic sensing purpose. It has two fibres tightly buffered inside a squared protection layer. The NanZee Reinforced Strain Cable has four steel braids armouring around the optics fibre. Outside the steel braids there is a protection tube which makes this cable most robust one in the four tested strain cables. The loose buffer telecomm cable is used as temperature sensing cable. It has 8 coated single mode fibres floating within a hard tube which is filled with gel. The gel makes the external strain placed on the tube not able to be directly transferred to the fibre and therefore isolating strain effects. Due to the robust design, all tested sensing cables are ideal for harsh environment applications such as pipeline monitoring and burial in the solid.

Table 1. The tested strain cables and temperature cable

Cable	Fujikura reinforced Cable	Brugg Strain Cable	Tight buffer telecomm cable	NanZee Reinforced Strain Cable	Loose buffer telecomm cable
Details	Steel wire reinforced cable embedded with four single mode fibres	One up buffered optical fibre with robust outer sheath	Very compact tightly-jacketed cable	Tight buffered single mode fibre	Excel loose tube cable
Sketch					
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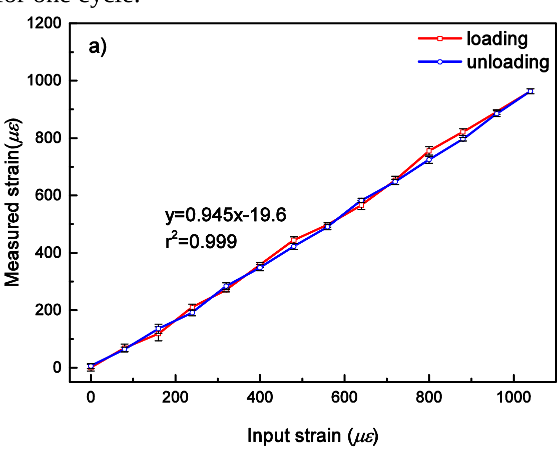
3.2 *Strain calibration results*

During strain calibration, the tested strain cables were pre-strained to 1000$\mu\varepsilon$. Then, they were loaded 1000$\mu\varepsilon$ more and unloaded back to pre-strain condition in a step of 100$\mu\varepsilon$ using the strain calibration rig. At each strain condition, three measurements were recorded with Neubrex (NBX-5000) BOTDR analyser. The analyser was set with 0.5m spatial resolution and 0.05m sampling resolution. Strain recorded at cable pre-strained condition was used as a baseline reading.

The measured strain along the holding sections of four tested strain cables were averaged and plotted against the input strain change (Figure 4). The averaging was made over 60 data points (i.e. averaged over the length of 1m effective length with cables and readings were made three times). The error bars at each strain level was calculated as the standard deviation of all 60 data points.

The qualities of the tested four strain cables were then evaluated with four sensing parameters: C_ε, r^2, σ and ε_d. C_ε is the Brillouin frequency shift to strain conversional coefficient, r^2 is the coefficient determination of the best fitted line between measured strain and input strain value, σ represents measurement uncertainty which is the average of precision error calculated at different strain levels, and ε_d indicates slippage which is calculated as the difference between analyser measurement at pre-set cable condition and measurement after the cable is loaded and unloaded for one cycle.



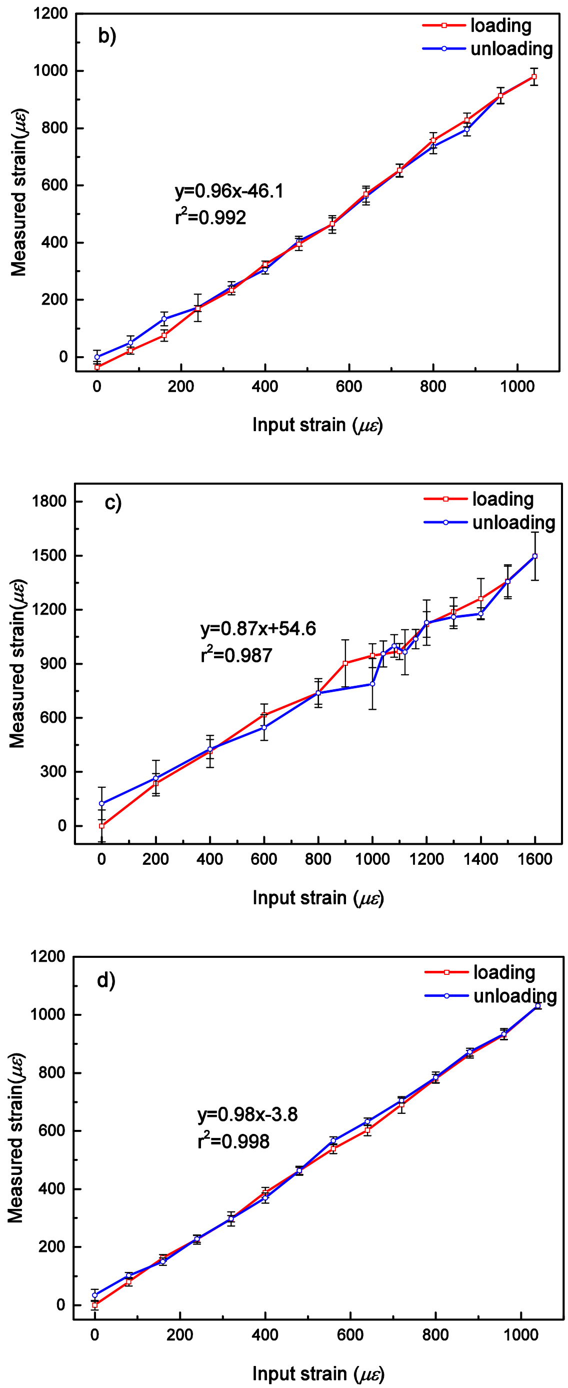


Figure 4. The analyser measured strain vs. input strain for a) Fujikura Reinforced Strain Cable, b) Brugg Strain Cable, c) Tight buffer telecomm Cable and d) NanZee Reinforced Strain Cable.

Table 2 compares the quality of the tested strain cables in regard of their sensing parameters. It can be seen that C_ε is in a range of 0.0435-0.049 $MHz/\mu\varepsilon$ for four tested cables, which indicates C_ε can vary at least 13% for different types of strain cable. The table also illustrates Fujikura reinforced cable and NanZee reinforced cable have relatively higher measurement accuracy and better measured linearity compared to that of Brugg and tight buffer telecomm cables. The reason of that is probably due to the robust cable reinforcement causes the sensing fibre in a very stable condition during strain process. The small ε_d of the Fujikura cable implies that this cable has little slippage effects which can be proved in various case studies(Klar et al. 2006). In summary, the Fujikura Reinforced Strain Cable shows the best sensing performance during this strain calibration experiment.

Table 2. The comparison of the four tested strain sensing cable

Cable	Fujikura reinforced Cable	Brugg Cable	Tight buffer telecomm Cable	NZ reinforced Cable
$C_\varepsilon(MHz/\mu\varepsilon)$	0.047	0.048	0.044	0.049
r^2	0.999	0.992	0.987	0.998
σ ($\mu\varepsilon$)	11.1	22.9	82.9	15.5
ε_d ($\mu\varepsilon$)	6	22	125	34

3.3 Temperature calibration result

In temperature calibration, 12m of temperature cable and 7m of Fujikura Reinforced Strain Cable were spliced together and immerged in the water bath. Water taken from a tap was heated and cooled in a range of 20°C~45°C, at 5°C interval. At each temperature level, three repeated measurements were taken by NBX-5000 analyser after the temperature was stabilized. The baseline reading was taken at 20°C.

Figure 5 plots the temperature readings of the analyser at every 5cm along a) temperature sensing cable and b) strain sensing cable. The readings were calculated as an average of three repeated measurements at each temperature level. It can be clearly seen that temperature cable shows larger σ_T (measurement fluctuation) than strain cable does. For example, in the baseline condition, σ_T is 0.42°C for temperature cable and 0.19°C for strain cable. In the later experiment, σ_T does not change a lot and stays at around 0.49°C for strain cable. However for temperature cable, σ_T is building up during later heating/cooling process. It increases from 0.42°C to about 2.34°C after the whole experiment has finished. One explanation is that with temperature change, the property of cable gel becomes instable. When temperature is decreasing, the hardening of the cable gel induces external strain to the sensing fibre and thus causes measurement fluctuation. Because in practice temperature is not changing very spatially, an average result over distance may be used in the future for temperate compensation.

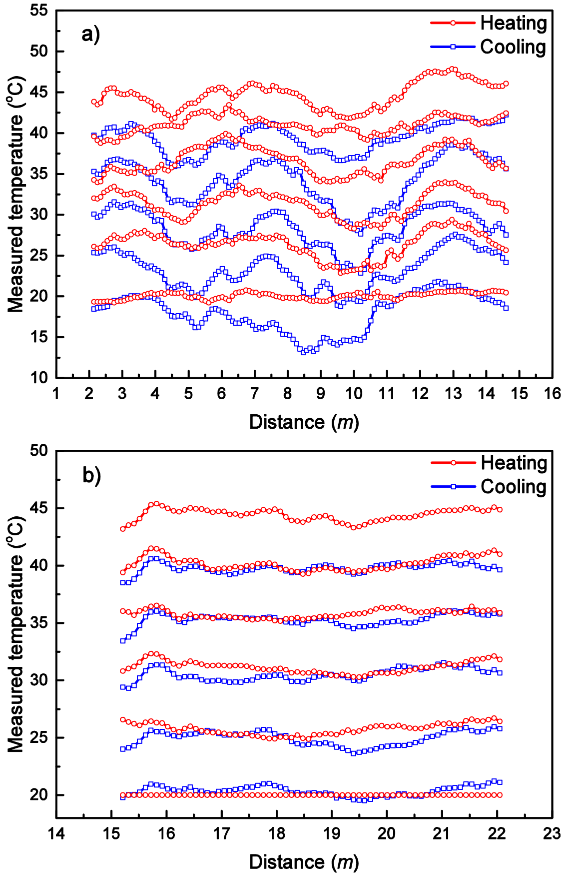


Figure 5. The average temperature measurement along cable length for a) temperature cable and b) strain cable.

Figure 6 presents the linear relationship of measured temperature plotted against temperature input. The strain cable shows no hysteresis while the temperature cable shows about 2.5°C hysteresis during the experiment. In addition, the measurement uncertainty for temperature sensing cable (2.22°C in average) is rather worse than that of strain sensing cable (0.75°C in average).

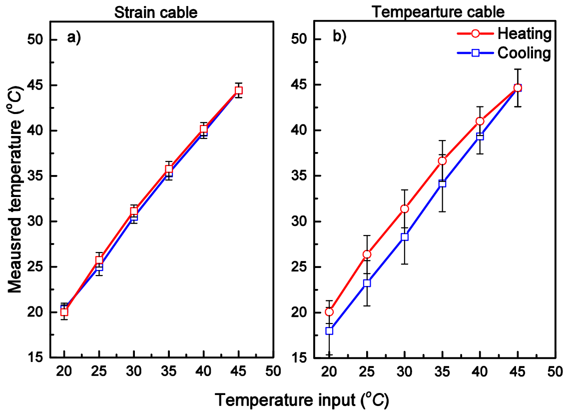


Figure 6. The linearity between analyzer measured temperature and input temperature for a) strain cable and b) temperature cable.

Temperature cable was then calibrated in a larger temperature range (5℃~85℃) with more heating/cooling cycles to investigate measurement hysteresis. Figure 7 plots the analyser measured temperature with regard to input temperature change for three continuous heating/cooling cycles. For all 3 cycles, σ_T is maximum at low temperature condition which again indicates that the hardened gel induces external strain to the sensing fibre when cooled. Hysteresis can be clearly seen in cycle 1, but almost disappear in cycle 2 and cycle 3, which implies that after one cycle of heating/cooling, cable gel property tends to stabilize and the changing gel property induced external strain becomes in the same pattern in short time.

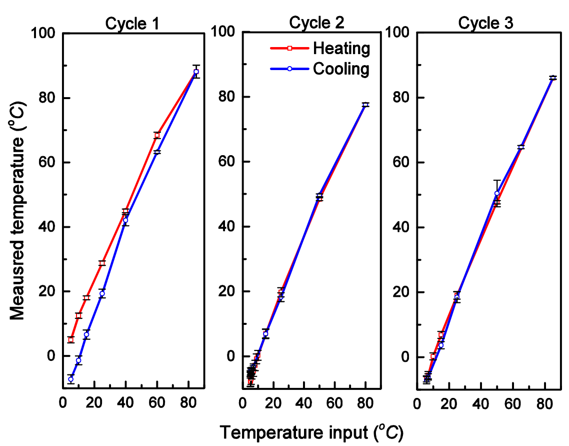


Figure 7. The linearity between measured temperature and input temperature for continuous three heating and cooling cycles.

4 CONCLUSION

In this paper, we presented a newly developed strain and temperature calibration platform for the distributed fibre optic sensor. Four types of tight buffered strain sensing cable were calibrated in the laboratory and the steel wire reinforced strain sensing cable was proposed as the best suited sensing cable considering its relatively higher measurement accuracy and little slippage occurred during loading and unloading test. Some of the strain sensing cable showed worse ability in strain measurements due to a low linearity between strain change and measured Brillouin centre frequency. Temperature cable was found out to have larger sensing hysteresis compared to strain cable which is probably due to the unstable property of the cable gel. After one cycle of heating/cooling, cable gel property tends to stabilize and temperature hysteresis was observed to be significantly minimized. However longer time effects on temperature hysteresis needs more investigation in the future.

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