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Strain and temperature calibration of Brillouin Optical Time Domain Analysis (BOTDA) sensing system

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Abstract. Instrumentation plays an important role in monitoring the performance of the geotechnical structures especially slope as it can be an effective approach for many unstable or potentially unstable. In the recent study, BOTDA interrogator is used to monitor the strain development on a laboratory soil slope model in order to assess the failure mechanism of residual soil slope under rainfall infiltration and surcharge loading. By understanding the concept of BOTDA technology which based on the Brillouin frequency shift (Δv_b), it possible to monitor changes in soil movement. Thus, the aim of the paper is to evaluate the parameter configuration of the BOTDA interrogator by determining both strain and temperature coefficients associated with the signal differences. The methodology presented as for acquiring the coefficients by calibrating the signal difference in terms of strain and thermal characteristics only for 12 ribbon Fujikura optical fibre sensor. As a result, the coefficient over a Brillouin signal for Fujikura optical fibre is 20 με and 1°C for strain and temperature respectively. Therefore, the raw data obtained by the interrogator which in Megahertz unit can be evaluated in term of strain and temperature with respect to the coefficients.

1. Introduction

A fully distributed sensing technology named Brillouin Optical Time Domain Analysis (BOTDA) and Brillouin Optical Time Domain Reflectometry has been proposed in 1980s by Horiguchi and Tateda (1) with one of the potential applications of this tool is to be used in monitoring the performance of slope stability. This modernized technology shows a lot of positive aspect rather than the traditional sensors due to its long distance measurement, high resolution and low cost of the optical fibres. The BOTDA technology adopts the stimulated Brillouin scattering (SBS) effect which is generated from the interaction of two ends of sensing fibre to capture the weak Brillouin backscattered signal. As the pumping light and continuous wave light travels down the fibre from both ends, a portion of Brillouin frequency is backscattered when the continuous wave light frequency differs from the pumping pulse light. The backward Brillouin scattering frequency is proportionally shifted due to strain or temperature difference along the fibre with respect to its return time of the signal (2).

The uses of distributed optical fibre technology have been extended to civil engineering applications especially in monitoring the structural health of infrastructures. Several early works of using distributed optical fibre sensor were studied through laboratory tests, included bending of the structural beam, and crack detection. Afterward, the development of the optical fibre sensing technology was proceeded to monitoring the behaviour of geo-structures; for instance, piled-foundation (3–5), slope monitoring (6–8) and tunnels (9).

Figure 1 illustrates the three-dimensional mechanism of Brillouin gain spectrum for stimulated Brillouin signal for a BOTDA system. As the BOTDA sensing system has been utterly responsive to the variation of temperature and strain along the cable, this characteristic has made the system performed distributed measurements. Therefore, the Brillouin shift profile of a medium can be obtained using the BOTDA sensing system as the stimulated Brillouin signal is a function of time and frequency. Then, the measurands (strain/temperature) were computed as a result of the translated frequency shift, (vB) via the use of quantified calibration coefficient of an optical fibre. The captured profiles (frequency shift difference, vB) are then can be interpreted as the medium overall deformation or temperature readings as stated in Equation 1 (10).

$$dv_b = \frac{\partial v_b}{\partial \varepsilon} d\varepsilon + \frac{\partial v_b}{\partial T} dT \qquad [1]$$

where the constants for strain, $\partial v_b / \partial \varepsilon$ and temperature $\partial v_b / \partial T$ are tabulated in Table 1. It is noted that the coefficients are the optical properties and slightly differs due to the coating material (10).

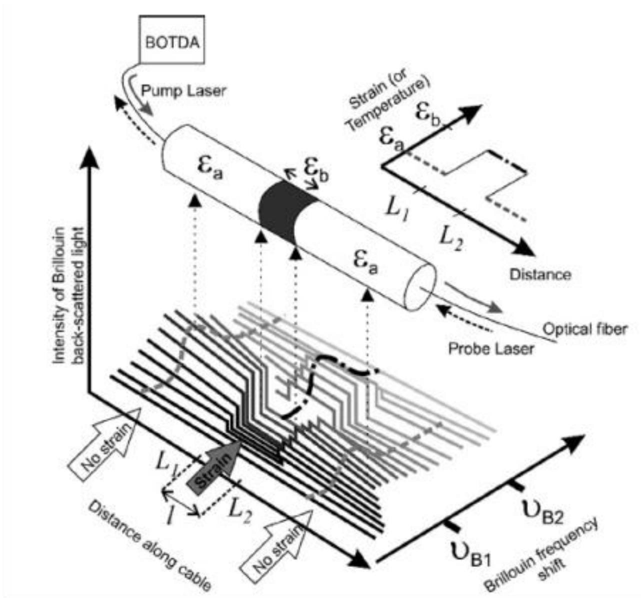

Figure 1. The stimulated Brillouin gain is maximized when the frequency difference between pump and probe light equals the local Brillouin frequency shift (BFS) (11).

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Table 1. Brillouin shift strain and temperature coefficient (10).

$\partial v_b / \partial \varepsilon$	$\partial v_b / \partial T$
57.9 GHz at 1320 nm wavelength	1.18 MHz/°C at 1320 nm
50.6 GHz at 1550 nm	1.00 MHz/°C at 1550 nm
49.3 GHz at 1550 nm	1.0773 MHz/°C at 1550 nm
55.7 GHz at 1320 nm	1.59 MHz/°C at 1320 nm

In this study, OZ Optics' Foresight™ series of fibre optic Distributed Strain and Temperature Sensors (DSTS) BOTDA interrogator is used to evaluate the strain and/or temperature for optical fibre sensing system. The BOTDA interrogator can be connected to 2 loops of fibre via the optical connectors via 2 channels. The configuration features for DSTS are shown in Figure 2. Firstly, parameter configurations are needed to embark the testing. The parameters are divided into three (3); base set up, fibre and scan configurations. As for the base set up and scan configurations, the manual has provided a basic guideline to decide on the selections. However, for the optical fibre set up, calibration testing is firstly performed to obtain the correct coefficient and temperature to be keyed in the system.

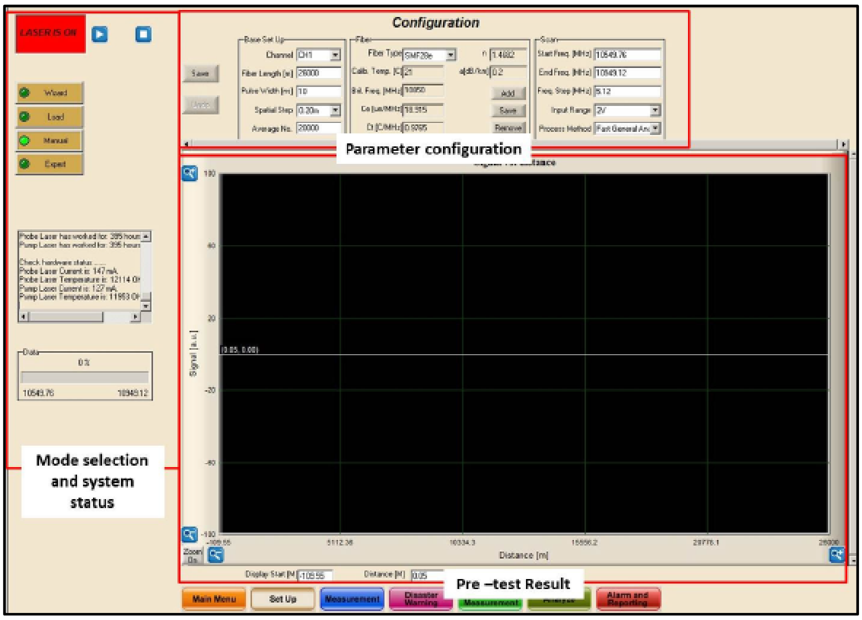

Figure 2. The configuration (setup) page for DSTS (12).

1.1 Set up on parameter configuration (12)

Basic set up consist of the channel, fibre length (m), pulse width (ns), spatial step and average number. The optical fibre was connected to DSTS sensor systems by connecting the optical connectors to the assigned optical port. There are two channel port: channel 1 and channel 2 where channel 1 is selected from the drop-down menu since fibre optic is connected at port 1. Then, value of the fibre length is entered slightly longer than the actual length of the fibre. If the entered value grossly different from the actual fibre length, it will affect the measurements analysis especially when a long fibre is used but short fibre is specified in DSTS, it will results in corrupted measurements as multiple pulses could be in the fibre at one time.

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Pulse width, spatial step and average number related to each other and mainly depends on the fibre length. The pulse width related to measurement range and this parameter specified the width of the probe pulse in nanoseconds (ns). The value of pulse width corresponding to the optical fibre length shown in Table 2 where by choosing the correct pulse width, the spatial resolution of the can be achieved. From Table 2, it can be shown that longer pulse width (example: 500ns) carry more energy than shorter pulse (example: 1ns) as it gives larger signals which give sufficient energy for long fibres. Basically, choosing appropriate pulse width to improve the signal to noise ratio of the optical fibre. Hence, 10ns is selected throughout the measurements analysis as provided in the guideline for a fibre length of 15m – 20m which gives the best balance between signals and spatial resolution.

Table 2. The relationship between pulse width and fibre length.

Pulse Width (ns)	Fibre Length (m)
1	0.1
10	1
500	50

The spatial step is closely related to pulse width where this parameter determines the measurements distance for optical fibre. The value of spatial can be selected from the drop-down menu within a range from 5cm up to 10m. A spatial step of 5cm was chosen since smaller spatial step give more data points collected along the fibre and better precision of measurement of analysis for both strain and temperature can be made. Then, an average number of 65000 was entered in the DSTS configuration. The higher averaging number also improve the signal to noise ratio as this parameter related to the average's number of scans for the measurement of the fibre optic

The configuration involved under scan parameter are start frequency (MHz), end frequency (MHz), frequency step (MHz), input range and process method as shown in Figure 2. Basically, start frequency and end frequency are the low end and high end of the frequency scan range respectively. Both start and end frequency can be determined based on initial scan results, and the appropriate scan range is set afterwards. It is crucial to set an appropriate scan range as an unnecessarily very low start frequency and very high end frequency will needlessly increase the measurement time. Whereas, the configuration of the frequency step related to the increment in the frequency between successive scans and 7.86MHz was entered for an increments in the frequency of 10400MHz (start frequency) and 11300MHz (end frequency).

Next parameter is the input range. The value of the input range can be selected from the drop-down menu: 50 mV, 100 mV, 200 mV, 500 mV, 1 mV, 2 mV, 5mV and Auto. Basically, the analog signal produce by the sensor system (DSTS) must be digitized to produce data that can be processed. The digitizer's input range should match the range of the analog signal to reduce the signal's noise. The digitization range cannot be too large and too small as it affects the measurement. The 500 mV of input range was given through the Auto selection from the drop-down menu where the value was automatically selected by the DSTS software in order to optimize and digitize the signal for 15m-20m fibre length. Lastly, a process method. There are several options for processing the collected data: (1) peak search, (2) fast analysis and (3) fast general analysis. These options depend on the user whether to process the data in term of time or accuracy. Usually, for a faster analysis, usually peak search and fast analysis are chosen however the analysis not very accurate. Faster processing speed may be appropriate when initially configuring and testing a system whereas a slower but more accurate processing method more desired when making critical measurements. Thus, the general analysis was chosen for processing the data as this method provide an accurate analysis of the Brillouin spectrum.

2. Materials and method

For this study, 12 –ribbon Fujikura is used to be the strain sensing cable (refer to Figure 3). The cable comprises 12 fibres of different colour coded coatings. The size of 12 ribbon fibre is 3mm in width and approximately 0.3mm thickness. Due to the larger surface/contact area, the optical fibre is suitable to be the sensing cable for the direct embedment in the soil mass. However, the cable is prone to damage because of no outer jacket for better protection (13).

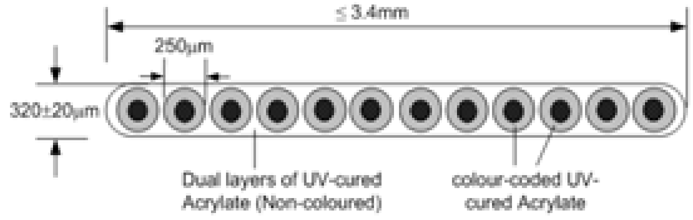

Figure 3a. A schematic diagram of sensing fibre (13).

Figure 3b. 12 ribbon Fujikura.

To get the accurate value of strain and temperature, the input for parameter configuration need to be entered correctly since different type of fibre optic have different value of coefficient of strain and temperature. Thus, calibration process is crucial before any measurement are taken. Thus, this paper shows the lab procedure which is designed to calibrate the Fujikura optical fibre in order to evaluate the value of coefficients since there is no established manual to calibrate this particular fibre optic.

2.1. Calibration method for the coefficient of strain

The objective of the calibration is to determine the relationship between Brillouin shift frequency and measured strain. The fibre optic was calibrated using 3m length fabricated strain rig set-up with a ball-bearing guiding tracks on the left side. The other side is a fixed clamp and the strained fibre section can be adjusted to the maximum length of 1.5m. The set-up also can be connected to 'S' type load cell as shown in Figure 4 which can be incorporated at the latter end side of strain rig set-up similar as a conventional tensile load test. From the tensile load test set-up, we can determine the maximum tensile capacity of the optical fibre and evaluate the Young Modulus, E of the fibre cable. For the set-up, the capacity of 'S' Type Load Cell is 500lb and the reading of tensile force was connected to digital load meter (TC-31L). A total of 19 m of fibre length was prepared for the calibration test and the strained section at the position of 8m and 9m was determined as the sample length. Initially, the baseline reading is configured and followed by pulling every 1mm and the measured strain was acquired from the BOTDA interrogator. The tensile force was simultaneously read from the digital load meter.

2.2. Calibration method for the coefficient of temperature

Another parameter configuration of the optical fibre is the temperature coefficient. The fibre optic was calibrated using Memmert water bath tank with a dimension of 8.1m length, 5.1m width and 2.8m height where the set-up of the calibration are shown in Figure 5a and 5b respectively. The thermal water tank consists of a heating bar inside the tank and temperature controller at the front side. A total of 20m fibre length and about 5m length of fibre has been embedded in the water bath which was in between 8m to 12m of overall length. The temperature at 23 degree Celsius (tap water) was used as a baseline reading. In the experiment, the water was heated up in five stages. The value of temperature was set with an increments of 10˚C and the strain data were recorded every temperature reading; which were started from 31, 41, 52, 61 and 72 degree Celcius. Only 5 readings were taken to evaluate the Brillouin frequency at the submerged sections were averaged (averaging was made over 40 points over effective length of 2m) and was plotted against temperature change to obtain the thermal coefficient that would be one of the inputs for the configuration set-up of BOTDA system.

Figure 4a. Fibre optic tensile load test.

Figure 4b. ‘S’ Type Load Cell.

Figure 5a. Memmert Water Bath.

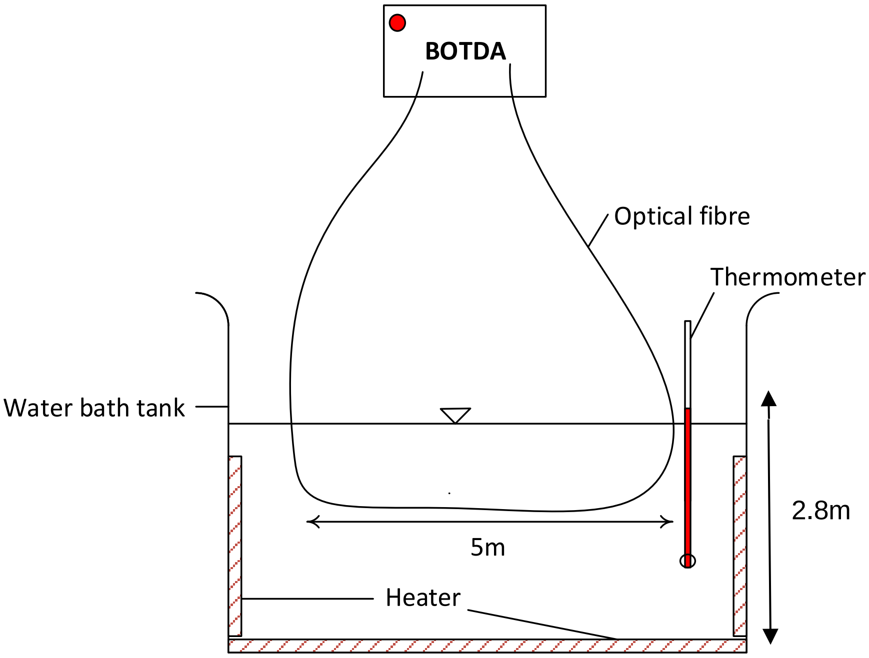

Figure 5b. Schematic Diagram for Temperature Calibration set-up.

3. Result and Discussion

This section discussed the result of the optical fibre calibration regards to the configuration set-up as in Figure 2. The strain and temperature coefficient were obtained by evaluating the relationship of 1 micro strain (με) and 1degree celcius (˚C) with respect to Brillouin frequency shift of 12 ribbon Fujikura cable.

3.1. The Coefficient of Strain (C_ε)

The calibration experiment was only performed up to 10mm elongation and the strained section was from 7.7m to 8.7m. Any section of fibre can be selected and since the calibration testing occurred in the middle of the fibre length, 7.7m to 8.7m is an appropriate length. The strain data afterward (10mm to 15mm) were not consistent probably due to slippage has occurred between the optical fibre and the coating itself. As for the measurements obtained by BOTDA are centre weighted averages (13) of the strain, the middle part of the strained sectioned (refer to Figure 6) were taken into consideration to obtain a consistent frequency readings. Then, the constant part were averaged over 10 points and a relationship graph of strain versus frequency is plotted as shown in Figure 7. Therefore, the strain coefficient corresponded to 1 MHz of the signal is 20 micro strain (με). The strain coefficient was then used to be an input parameter at configuration set-up of BOTDA
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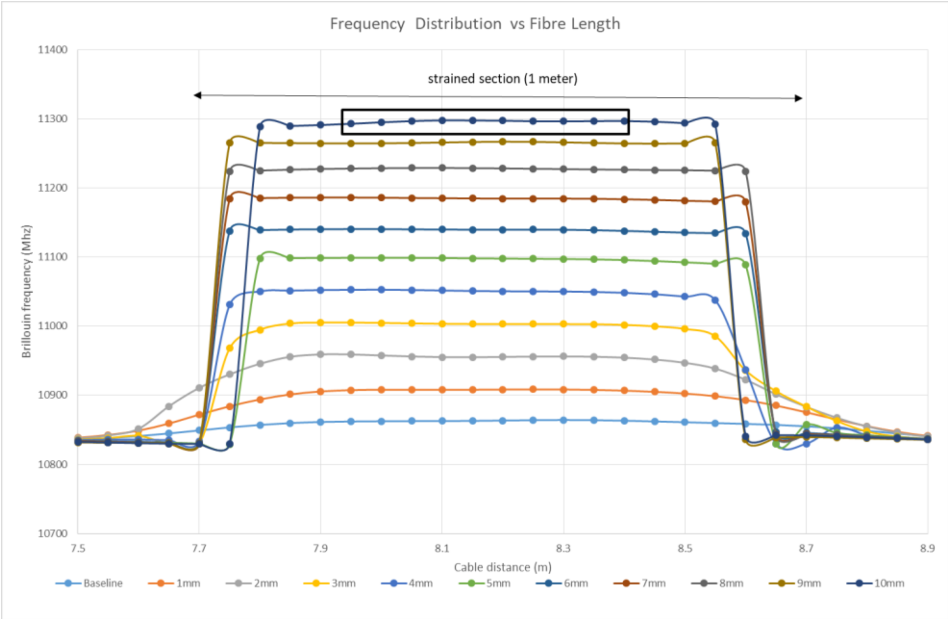

Figure 6. Frequency distribution against fibre length.

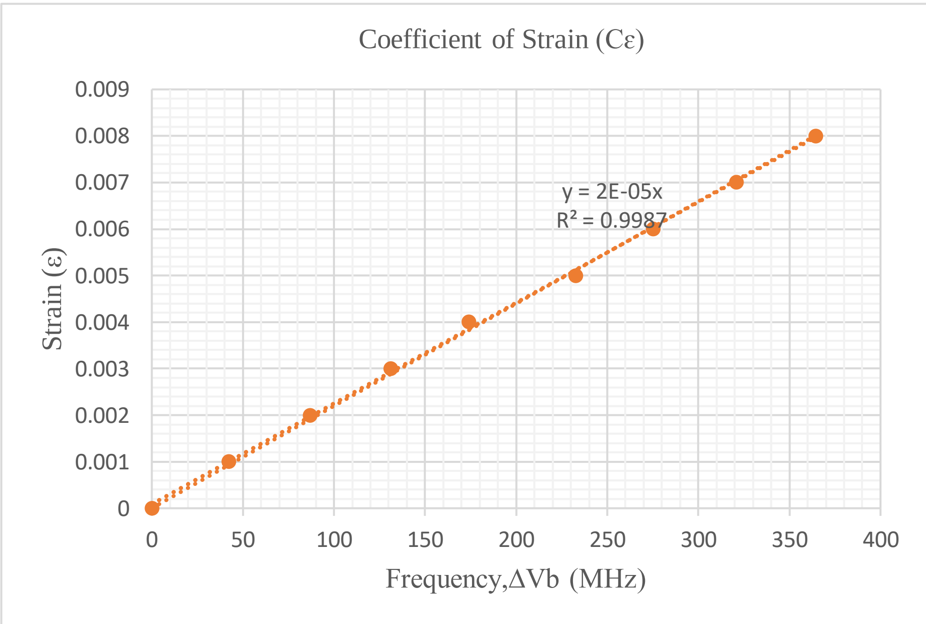

Figure 7. Graph of the relationship between frequency and strain.

3.2. The coefficient of Temperature (C_T)

As for the temperature coefficient, a baseline reading was assigned at a temperature of 23˚C. The averaged value of frequency (v_b) was calculated by taking the average of constant reading of frequencies which were represented a submerged part of the optical fibre (only consider 2m of submerged length as illustrated in Figure 8). The cooling process was also made to complete the heating-cooling cycle until the water reached the original tap water temperature. Figure 9 exhibits the linear relationship of temperature difference against the Brillouin frequency shift, Δv_b. The coefficient of temperature obtained is 0.9977 which is approximate to 1 ˚C/MHz.

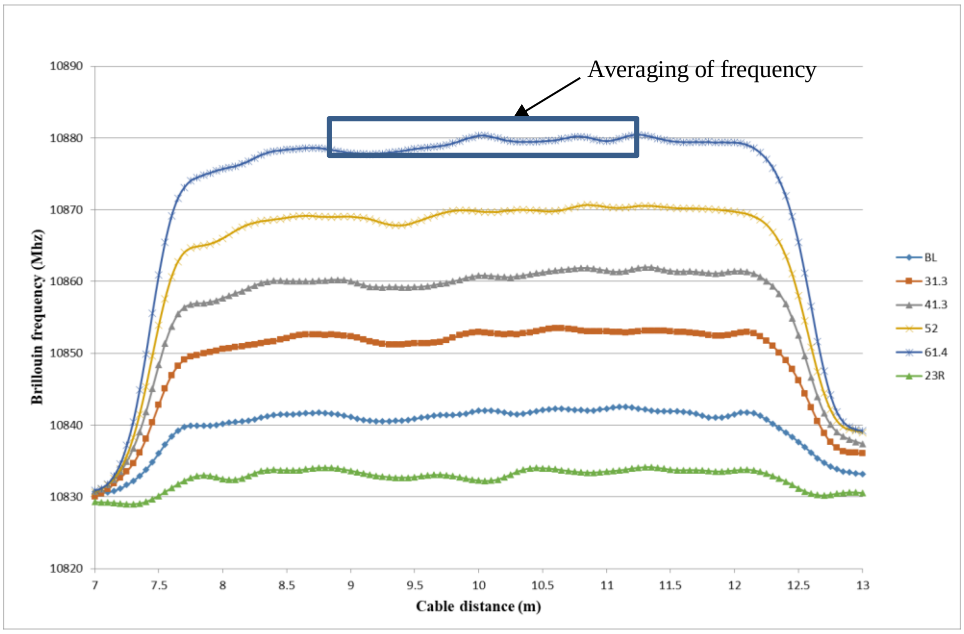

Figure 8. Frequency distribution against fibre length (temperature).

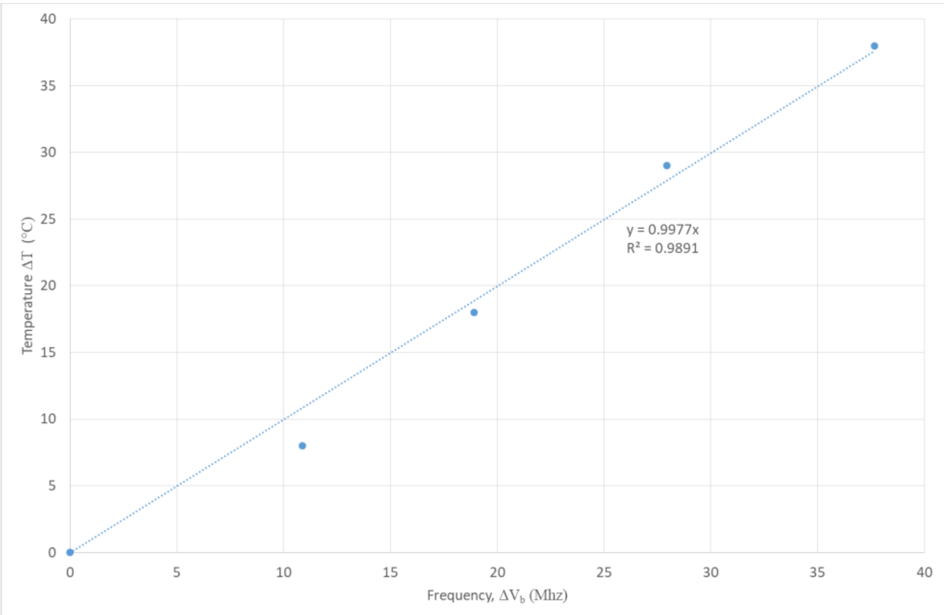

Figure 9. Graph of the relationship between frequency and temperature.

4. Conclusion

As been mentioned previously, the BOTDA system is able to measure both strain and temperature of the tight-buffered optical fibre and this advantage has made the lengthy optical fibre is a distributed sensor itself. Therefore, it is essential to understand the characteristic of BOTDA system and optical fibre sensor before any commencement of testing. It can be summarized that the coefficient of strain and temperature for 12 ribbon Fujikura optical fibre is 20 με and 1°C over a Megahertz of Brillouin signal respectively.

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