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Development of temperature-insensitive fibre bragg grating pressure transducer

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Abstract. In this work, the development of an aluminium diaphragm fibre Bragg grating (FBG) pressure transducer with temperature compensation strategy is presented. One of the big challenges for the applications of an FBG pressure transducer is the inconsistency in output wavelength due to temperature variations. This situation leads to huge uncertainties in pressure readings. The aim of this article is to present how to eliminate the effects of temperature variations to the pressure measurements. Two FBG sensors were used; namely as FBG 1 and FBG 2. These FBGs were bonded each one on the diaphragm and base surface of the pressure transducer. The strain readings by the FBG on the diaphragm was normalized by the FBG reference which was pasted on the transducer's base. This temperature compensation strategy was successful and the FBG pressure transducer was proven to be suitable for pressure measurement of gas with an average error of 2.32%. Besides, the result also shows that, for pressure ranging from 0 to 0.5 MPa, the FBG pressure transduced has sensitivity of 2.8485 nm/MPa with linear fitting coefficient of 99.97%.

Keywords. Fibre Bragg grating (FBG); pressure sensor; temperature compensation

1. Introduction

Pressure measurement is a crucial element in many industries such as petrochemical, oil and gas, hydraulic, power and energy, and aerospace [1]. Conventionally, electrical or mechanical pressure sensors have limitations in several applications such as harsh environments with serious electromagnetic interference (EMI), extreme temperature and pressure, hazardous chemicals or explosives matter [2, 3]. Recently, fibre Bragg grating (FBG) sensing as a new measuring technology, has become one of the most promising optical fibre passive device application [4]. FBG offers many advantages in terms of size and weight, high sensitivity, high reliability, immunity to electromagnetic interference and multiplexing capabilities [5, 6]; thus able to overcome the drawbacks from the traditional pressure sensor. By monitoring the shifting of Bragg wavelength, different kinds of measurands can be calibrated such as temperature, pressure [7], strain and displacement [5]. However, FBGs are sensitive to both temperature and strain related to pressure measurements [8, 9], so that temperature cross-sensitivity cannot be avoided. Thus, a differentiating procedure for temperature compensation is needed to address this issue, such as using a reference FBG, simultaneous measurement of strain and temperature, writing two FBGs in different diameters, and combination an FBG with a Fabry-Perot cavity [10, 11]. This paper will present the temperature compensation strategy for a diaphragm type FBG pressure transducer.

1.1. FBG pressure transducer working principle

A fibre Bragg grating (FBG) is an optical fibre sensor consists of a Bragg grating, '*written*' into the core of an optical fibre by phase mask procedure [12]. When a broadband light source is travelling through the grating of an FBG, a narrowband also known as Bragg wavelength is reflected back. The Bragg wavelength can expressed as [13]:

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

Based on Eq. 1, the reflected Bragg wavelength, $\lambda_B$is depends on the effective refractive index, n_{eff} of the fibre and the grating period, Λ. Meanwhile, the shift of reflected Bragg wavelength, $\Delta\lambda_B$ is sensitive to the axial strain, ε and change of temperature, ΔT; and it can be written as [13, 14]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - Pe)\varepsilon + (\alpha + \xi)\Delta T \tag{2}$$

where Pe is the photo-elastic coefficient (0.22) of the FBG [15], α is the thermal expansion coefficient and ξ is the thermo-optical coefficient.

In our design, to get the measurement only in strain, we apply two FBGs labelled as FBG 1 with the centre wavelength of 1543.966 nm and FBG 2 with the centre wavelength of 1550.418 nm. The FBG 1 was attached to the centre of diaphragm, while the other one was pasted on the base surface of the pressure transducer (figure 1). From equation (2), the shift of Bragg wavelength for both FBGs can be written as:

$$\frac{\Delta\lambda_{FBG1}}{\lambda_{FBG1}} = (1 - Pe)\varepsilon_{FBG1} + (\alpha + \xi)\Delta T_{FBG1} \tag{3}$$

$$\frac{\Delta\lambda_{FBG2}}{\lambda_{FBG2}} = (1 - Pe)\varepsilon_{FBG2} + (\alpha + \xi)\Delta T_{FBG2} \tag{4}$$

The FBG 1 will detect the change of strain and temperature simultaneously while the FBG 2 will act as a reference, which is only set to consider the change of the temperature. When the diaphragm undergoes deflection due to the applied pressure, the strain at FBG 1 occurs and the strain at FBG 2 is zero ($\varepsilon_{FBG2} = 0$). Both FBGs were in the same temperature condition ($\Delta T_{FBG1} = \Delta T_{FBG2}$), thus the effects of temperature variations in FBG 1 has been eliminated by normalizing the equation (3) with equation (4). The normalization can be written as:

$$\frac{\Delta\lambda_{FBG1}/\lambda_{FBG1}}{\Delta\lambda_{FBG2}/\lambda_{FBG2}} = \frac{(1-Pe)\varepsilon}{(\alpha+\xi)\Delta T_{FBG2}} + 1 \tag{5}$$

Figure 1 shows the location of FBGs on the pressure transducer. All FBGs were pasted using superglue. The base of pressure transducer was connected with 12 mm x 40 mm male air hose fitting that can be linked with the 12 mm female pneumatic coupler. In this paper, two experimentations have been performed; which are the pressurization of air in metal pipe without temperature compensation; and with temperature compensation strategy. Both experimentations were repeated at four different room temperatures.

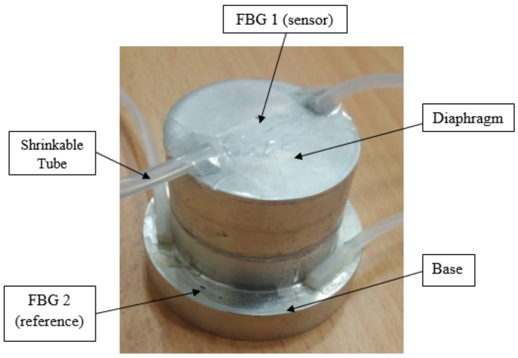


Figure 1. The bonding of FBGs on the pressure transducer.

2. Experimental setup

Figure 2 shows the schematic diagram of the experimental setup. The FBG pressure transducer was connected to a 1.37 x 10^{-2} m^3 cylindrical pressurized galvanized pipe that can withstand the pressure capacity up to 0.8 MPa. The pipe was pressurised through the air inlet by centralized air compressor. A traditional commercial Bourdon Tube type pressure gauge was attach to the pipe as pressure measurement reference. An Amplified Spontaneous Emission (ASE) was used as a broadband light source, and connected to port 1 of an optical circulator. Both FBG 1 and FBG 2 were connected to port 2 and Optical Spectrum Analyzer (OSA) was connected to port 3. Note that, the FBG 1 and FBG 2 were coupled in one-line. The OSA was connected to a PC, to monitor the reflected Bragg wavelength spectrum. The reflected Bragg wavelength spectrum from FBG 1 and FBG 2 were recorded and analysed.

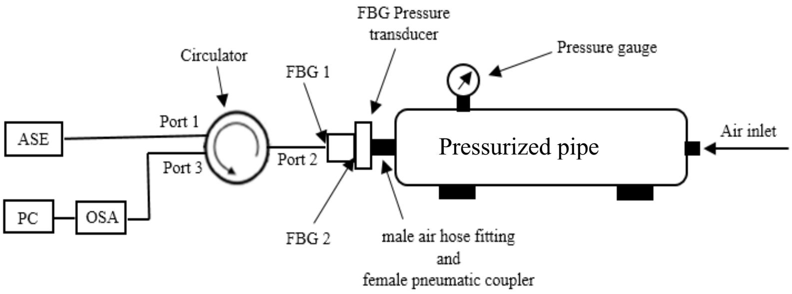


Figure 2. Schematic diagram of the experimental setup.

The experiment was conducted in four different room temperatures, which were randomly set up by manipulating three air-conditioning (AC) units set as AC1, AC2 and AC3. The different setup for room temperatures can be explained graphically by the laboratory layout shown in figure 3 (a–d). For each condition, the settling time was set at approximately 30 minutes until the temperature reading became consistent prior to the experimentation. A digital temperature meter was used to monitor the room temperature.

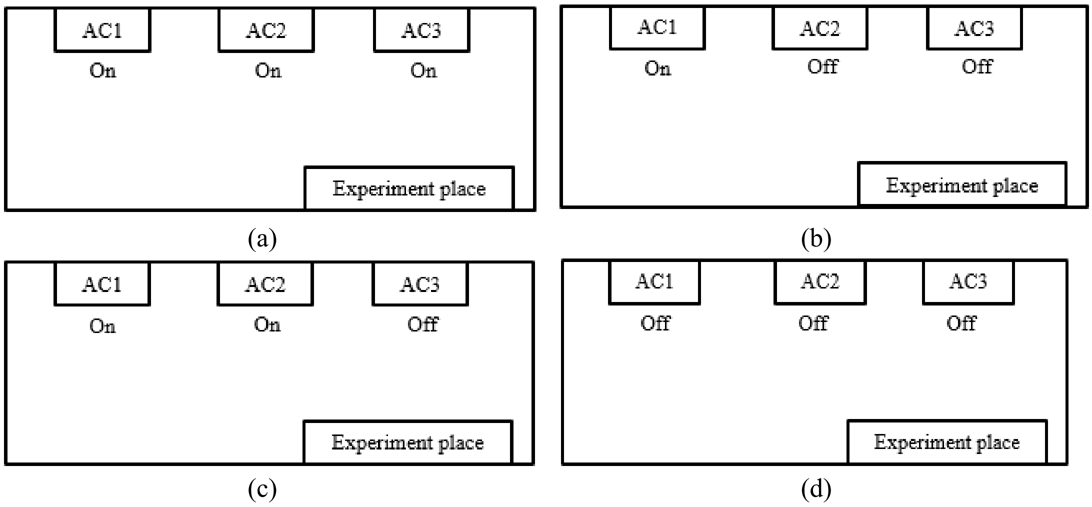
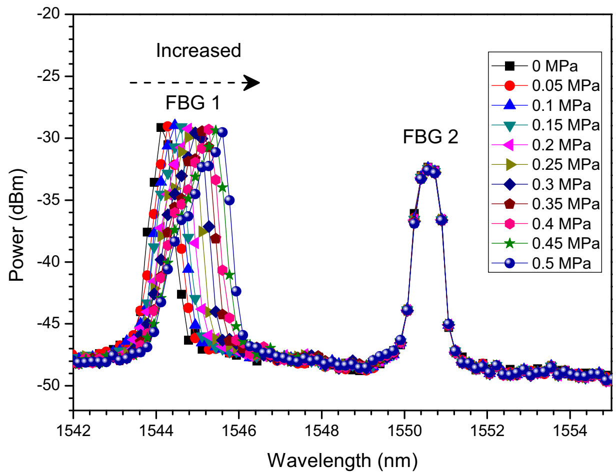


Figure 3. AC setup for four different room temperatures.

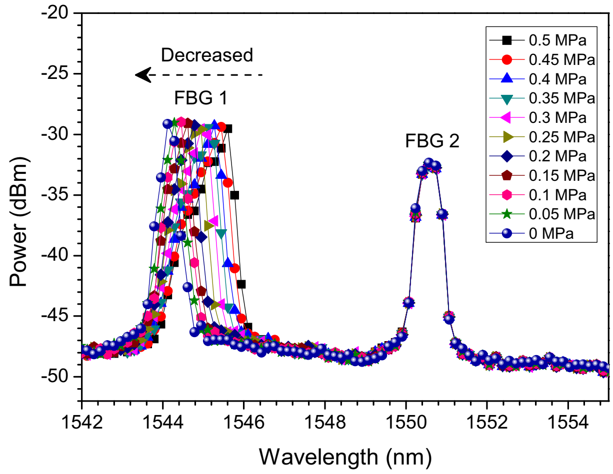
3. Results and discussion

3.1. Variation of Bragg wavelength at constant room temperature

Figure 4 shows the reflected Bragg wavelength at constant room temperature for both FBGs due to increased and decreased pressure. The pressure range for this experiment is from 0 MPa to 0.5 MPa with an increment of 0.05 MPa. When the pipe was pressurized, the diaphragm was deflected and cause a tension elongation on FBG 1, therefore the Bragg wavelength was observed shifted to the right gradually. Similarly, when depressurized, the reflected Bragg wavelength of FBG 1, shifted to the left. However, there was no significant shift were observed for FBG 2 spectrum.



(a)



(b)

Figure 4. The Gaussian Bragg wavelength shift during (a) increasing pressure and (b) decreasing pressure.

3.2. Experimentation at different room temperatures

To assure the room temperatures were consistent during the experimentation, a special test was carried out. For all AC setup as in figure 3, the Bragg wavelength readings of FBG 1 and FBG 2 were recorded in 30 minutes with an increment of 5 minutes. Figure 5 shows the Bragg wavelength for FBG 1 and FBG 2 at temperature setting as in figure 4a; whereby after 30 minutes, the temperature settled at 22.9°C. The spectrums for FBG 1 and FBG 2 reveal no significant changes, thus indicates that the wavelength readings for the FBG were steady at constant temperature. The same procedure was repeated for the other 3 AC setting, as in figure 3b, c and d. Figure 6 shows the summary of wavelength readings for both FBGs at four different room temperatures which are 22.9°C, 23.8°C, 25.9°C and 27.8°C . From the results, it can be seen that when the temperature changes, the wavelength readings also change, however, the wavelength readings will not change at constant temperature.

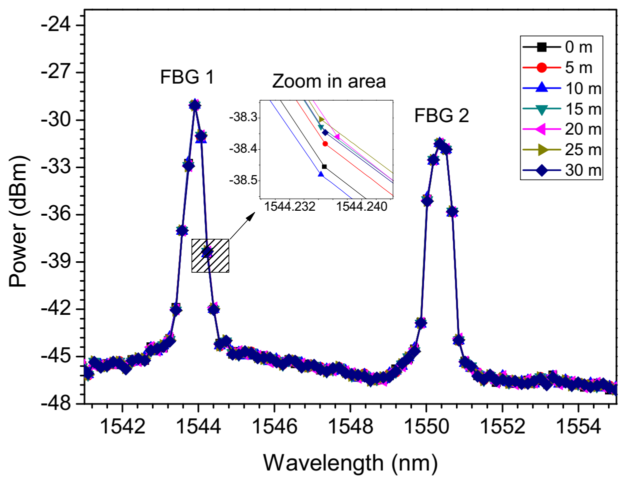
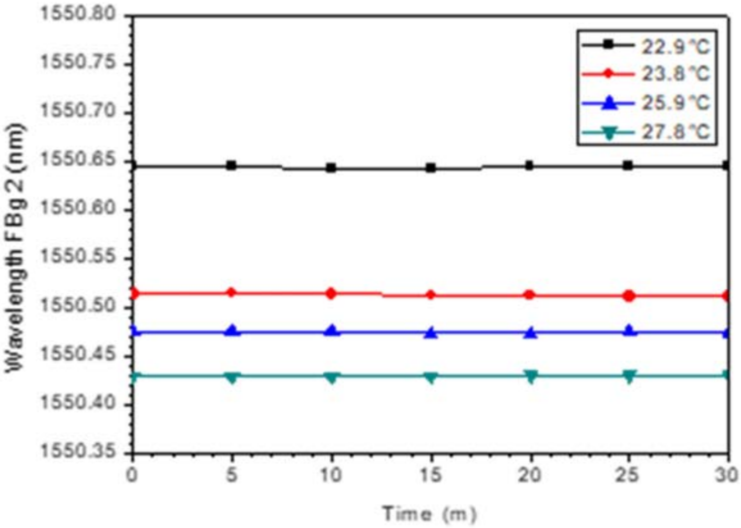
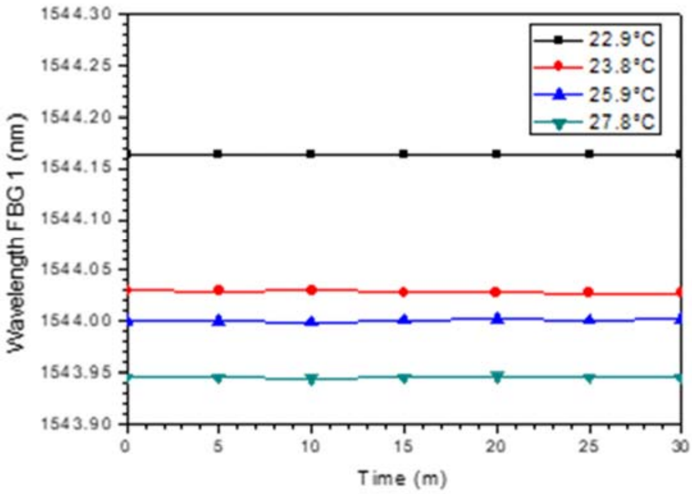


Figure 5. Wavelength readings for FBG1 and FBG2 at constant temperature (22.9°C), acquired for 30 minutes (with 5 minutes increment).



(a)



(b)

Figure 6. Wavelength readings for both FBGs at different room temperatures (a) FBG 1 and (b) FBG 2.

Next, the experiments for with and without temperature compensation methods were carried out. The data from both methods were validated with the conventional pressure gauge and the percentage error were calculated. Before the experiments were executed, the FBG pressure transducer needed to go through the calibration process to check the accuracy and traceability of the measurement. After the analysis, the response of both FBGs were found to be consistent. Figure 7 shows the results obtained from the repeatability test. From the results, it can be seen that the reflected wavelength of both FBGs at four different room temperatures was shifted when the pressurized pipe was pressurised. The wavelength trend of FBG 1 was increasing linearly and has an average sensitivity of 2.8485 nm/MPa with the good linear fitting coefficient is 99.97% but FBG 2 remains constant with the increase in pressure. However, both FBGs shows wavelength variation at different room temperatures. Therefore, it can be proved that both FBGs were sensitive to the temperature changes.

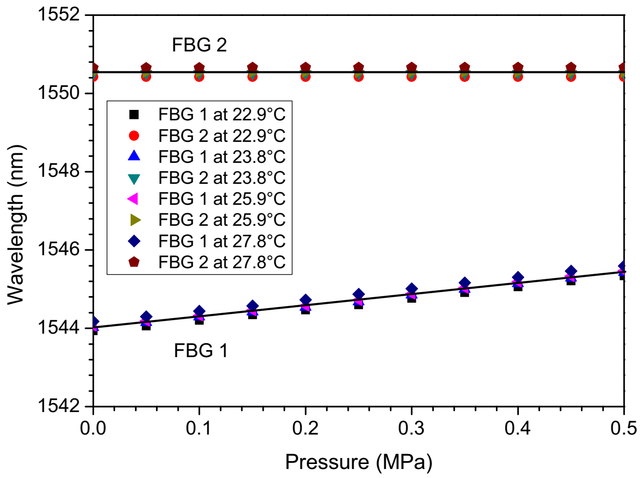
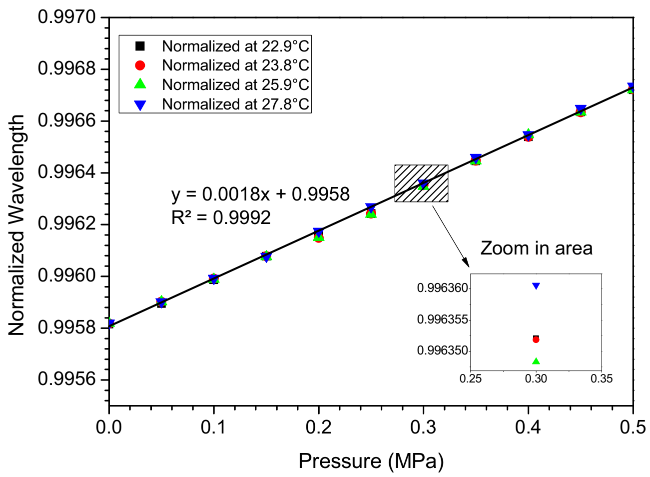


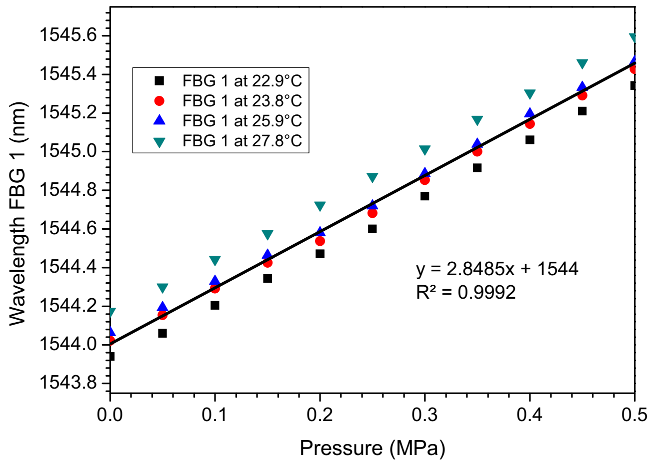
Figure 7. The repeatability tests of the pressure transducer at four different room temperatures.

3.3. FBG transducer calibration test

The FBG pressure transducer with and without temperature compensation strategy were calibrated with conventional Bourdon Tube type pressure gauge. For experimentation with temperature compensation, an equation was obtained by linear fitting of the normalization between the average of Bragg wavelength FBG 1 and FBG 2. Meanwhile, the equation for case without temperature compensation method was obtained by linear fitting of average Bragg wavelength of FBG 1 only. The linear equation for first method is y=0.0018x+0.9958 while for second method is y=2.8485x+1544 as shown in figure 8.



(a)



(b)

Figure 8. Two equations were obtained by linear fitting (a) with temperature compensation and (b) without temperature compensation.

These linear equations were used to convert the wavelength readings to the pressure readings. Ten samples reading from 0.05 MPa to 0.5 MPa with increment of 0.05 MPa for FBG pressure transducer were compared with conventional pressure gauge readings at four different room temperatures for FBG transducer with and without temperature compensation methods. Figures 9 and 10 show the recorded measurement. From the result, the average error for first and second methods were 2.32% and 16.51%, respectively.

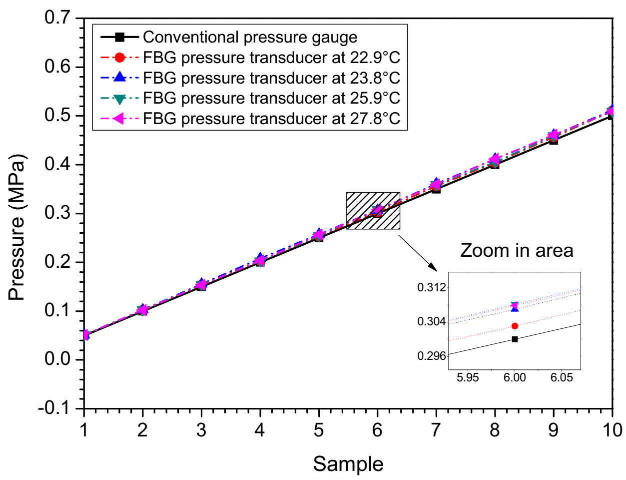


Figure 9. Calibration results for FBG transducer with temperature compensation method.

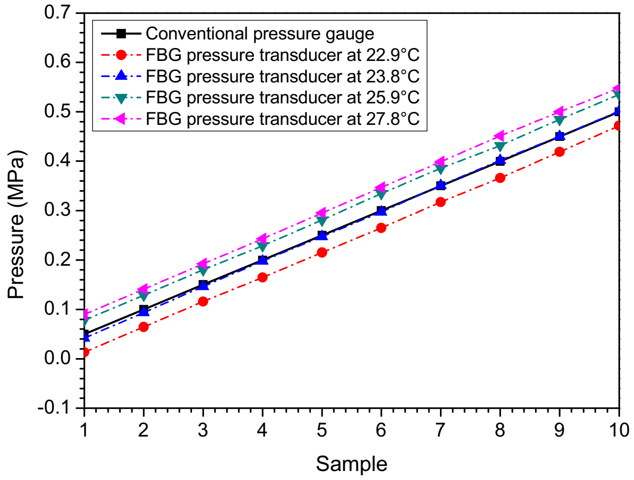


Figure 10. Calibration results for FBG transducer without temperature compensation strategy.

5. Conclusions

This paper presents the calibrations of an aluminium diaphragm type FBG pressure transducer for pressure measurement. The sensitivity of the FBG pressure transducer was determined and found to be 2.8485 nm/MPa with good repeatability. In addition, the linearity of the FBG pressure transducer is good with a fitting coefficient of 99.97% in a pressure range from 0 to 0.5 MPa. Moreover, to avoid the inaccurate pressure measurement which caused by temperature change, two FBGs were used. FBG 1 was attached on the centre diaphragm while FBG 2 was attached on the base surface of the pressure transducer. In conclusion, an average error between actual pressure readings and FBG pressure transducer readings for the first method was found to be 2.32%, which is significantly less the second method with an average error of 16.51%.

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