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Development of Fibre Bragg grating (FBG) dynamic pressure transducer with diminutive voltage inconsistency

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Abstract. In this work, a diaphragm-type Fibre Bragg grating (FBG) dynamic pressure transducer was designed and developed. Pressure transducer in this study consists of elastic thin metal diaphragm which acts as a primary sensing element; and integrated with an FBG sensor for the secondary sensing element. In the common match filter interrogation system, converting optical signal to voltage is the challenging due to voltage reading inconsistency, which would cause variation in pressure reading. New alternative arrangements of matched filter interrogation system are used to address the issue. For automated pressure measurement, the optical signal from FBG was converted into voltage by using the proposed arrangement of matched filter interrogation system**.** Additional FBG was added as reference sensor which installed in the system for detection the change of broadband light source. Reduction of voltage inconsistency was achieved by normalizing the voltage reading from sensor with the voltage reading from reference FBG. The result shows that the FBG pressure transducer is proven to be suitable for pressure measurement of gas or liquid with an average error of 5.348%. Furthermore, the FBG sensor has a good linearity with a linear correlation coefficient of 97.29% in pressure measurement.

1. Introduction

Recently, increasing interest in worldwide industries towards the application of Fiber Bragg grating (FBG) in sensing technology has brought to the rapid development and deployment of optical sensors especially in the monitoring of temperature and strain. FBG has a number of advantages, such as relatively small size and long life span. Besides, it is also inexpensive to manufacture, lightweight, multiplexing ability, self-referencing with a linear response, ease of installation, durability and immune to electromagnetic interference (EMI) [1-4]. Moreover, a pressure quasi-distributed measure can be realized by multiplexing in one single optical fiber to provide multiple FBG sensing elements without the need of installing a huge amount of strain gauge [5]. Sensing process in extremely harsh environments such as explosive gas exposure setting, high-temperature combustion chamber, and environment which contains high electromagnetic interference is feasible by using FBG sensors due to its passive nature. Although naked FBG sensor is fragile, an approach to encapsulate the FBG sensor could solve the problem by adding carbon fiber for reinforcement and solidified by epoxy resin with encapsulation technique [6]. The encapsulation technology protects the fiber from the severe environment in mounting processing without influencing the transmission of the strain applied to the FBG [7, 8].

In recent years, various types of the FBG-based sensor [9, 10] has been developed. Vengel Rao Pachava et al. [11] used the longitudinal FBG deformation principle by the transverse deflection of a diaphragm which induced an axially stretched-strain along the length of the FBG thereby creating a red shift of Bragg wavelength with the increased pressure. However, according to Frantisek Urban et al. [12], a longitudinal FBG's deformation will result in bigger optical signal wavelength displacement (FBG central frequency moves from 10 to 30 nm). They also emphasized that, by using the method of pressing the FBG laterally to obtain an ellipsoidal fiber cross-section shape only, will generate a maximum of 300pm spectrum peak spread.

In 2008, Zhang et al. [13] has reported their new FBG pressure sensor based on a flat diaphragm with enhanced responsibility by using a single FBG and an L-shaped lever with a curve of Archimedes spiral. It achieved ultrahigh sensitivity, 244 pm/kPa and reduced temperature sensitivity of 2.8 pm/^{o}C. The L-shaped lever is made up of quartz glass and laser machine. It requires high precision and the sensor design will be complicated compared to conventional diaphragm transducer. In the research works [13, 14] temperature was compensated because a temperature cross-sensitivity can lead to inaccurate measurement result [15, 16]. Zhao et al. [17] proposed a solution to compensate the temperature by adding a reference FBG. Sengupta et al. [18] solved this problem by utilized two FBG in different diameter fibers and the combination of FBG with the Fabry-Perot cavity is reported by Lin et al. [19].

A conventional pressure sensor based on strain gauge, vibration wire, mechanics, and etc. [20, 21] are unable to adapt to the harsh environments and also impossible to realize the online monitoring for long distance. Therefore, the FBG based pressure sensors become important in recent researches [22, 23]. Several studies have proposed improvement to the pressure measurement sensitivity, such as embedding FBG in the polymer, soldering metal-coated FBGs on a free elastic cylinder, and attaching the FBG to a diaphragm [5, 24].

In this research work, an FBG pressure transducer was designed and applied for pressure measurement by attaching FBG on the diaphragm. However, there are a lot of challenges to make the FBG based pressure transducer possible for a robust pressure measurement. For example, the issue of optic signal conversion to the voltage signal by using photodetector (PD); which shows the significant inconsistencies in output voltage [25]. This has led to huge variation in desired readings. To overcome the problem, a new arrangement of optical components has been proposed. In this configuration, additional FBG was added to the system which acts as reference FBG in order to eliminate the variation of voltage. The proposed pressure transducer, works under constant room temperature and the temperature cross-sensitivity is not being considered.

2. Working principles of FBG

FBG sensors are produced by creating periodic variations in the refractive index of the core of an optical fiber by using a high energy optical source and a phase mask [26]. Figure 1 shows the internal structure of an FBG sensor. Reflection of certain wavelength occurs when the light is traveling at the Bragg wavelength, which is a grating feature and appears missing in the transmission spectrum also shown in the diagram below when the grating structure only allows wavelengths of light [27].

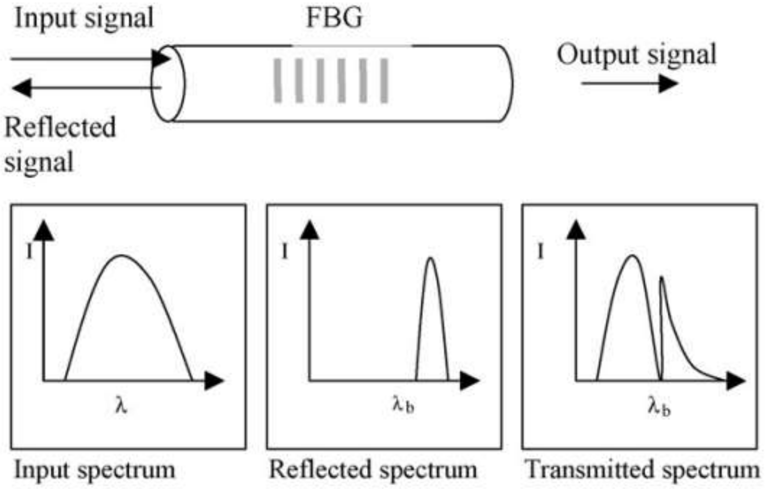


Figure 1. Transmission and reflection spectra from an FBG [28].

Bragg wavelength is a narrowband spectral output or a peak reflected wavelength from the FBG sensor after being illuminated by broadband light source and the light interacts with the grating of an FBG. The detection of local strain from a deformation is done through the variation of grating period and the reflected wavelength via the Bragg equation. According to the Bragg condition, the Bragg wavelength can be expressed in a well-known formula [29]:

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

where λ_B is Bragg grating wavelength, Λ is grating periodic spacing, n_{eff} is the effective reflective index of the fiber core. This formula is established by Nobel Laureate Sir William Lawrence Bragg in 1915 about diffraction of X-Ray from crystals and he expressed it into a simple mathematical formula.

The Bragg wavelength is sensitive to physical changes in the grating due to strain and temperature [30]. Thermal expansion in the FBG causes the effective refractive index and the spacing of the gratings to change simultaneously and produced a wavelength shift. This fractional Bragg wavelength shift for change in temperature ΔT can be written as [31]:

$$\frac{\Delta\lambda_B}{\lambda_o} = (\alpha + \xi)\, \Delta T \tag{2}$$

where α is thermal coefficient, ξ is the thermo-optic coefficient. Therefore, the strain effect on an optical fiber under a constant temperature, the Bragg wavelength shift $\Delta\lambda_B$ can be expressed in the form [32]:

$$\frac{\Delta\lambda_B}{\lambda_o} = (1 - p_e)\, \varepsilon \tag{3}$$

where $\Delta\lambda_B$ wavelength difference compared to original Bragg wavelength, λ_o. p_e is the gage factor or the effective photo-elastic constant and ε is the strain applied to the optical fiber. The linear change of the strain or pressure results in variation of FBG central wavelength.

$$p_e = \frac{n^2{}_{eff}}{2}\left[p_{12} - v(p_{11} + p_{12})\right] \tag{4}$$

where p_{12} are the silica photoelastic tensor components and v is the Poisson ratio. For an FBG central wavelength of 1550nm, typical strain sensitivity is approximately 1.2 pm/microstrain [33].

3. FBG interrogation system

There are two interrogation methods that are available for high-frequency vibration signals with FBG and suitable for pressure measurement; the edge filter detection and power detection methods [34]. In the edge filtering technique, an optical filter, which is also an FBG, is used for filtering. A broadband light source is supplied to FBG sensor through a three port optical circulator. Conversion between the intensity of light and voltage signal by a photodetector (PD) after the reflected light passed through the filter for signal acquisition [35]. The interrogation principle can be briefly explained in Figure 2. Bragg wavelength reflected from the FBG sensor which in tension is longer than original Bragg wavelength and shorter as the sensor is subjected to a compression.

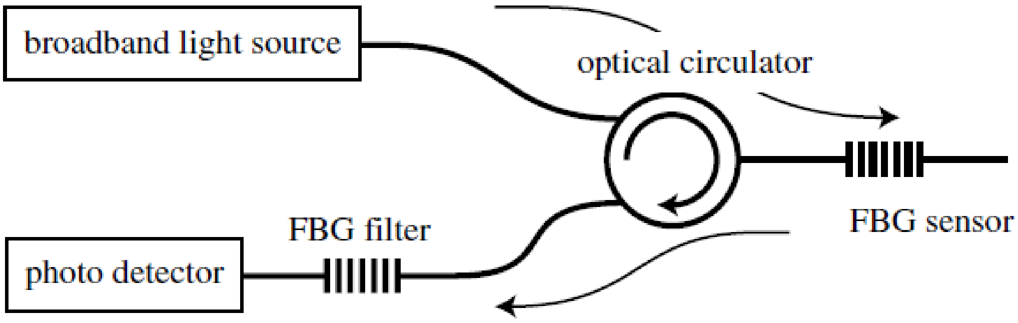


Figure 2. Matched edge filter arrangement for dynamic sensing by Tsuda [35].

Figure 3 show the schematic diagram of the movement of light in the circulator-based system. The matched edge filter interrogation method used in this experiment makes cheap interrogation method for FBG possible without sacrificing the accuracy measurement of the output voltage. The market product solid state FBG interrogator is expensive. Interrogation of FBG has enabling the optical signal to be converted to an electrical signal; therefore, the transducer can be easily connected to a data acquisition unit or an electronic controller, such as Programmable Logic Controller (PLC).

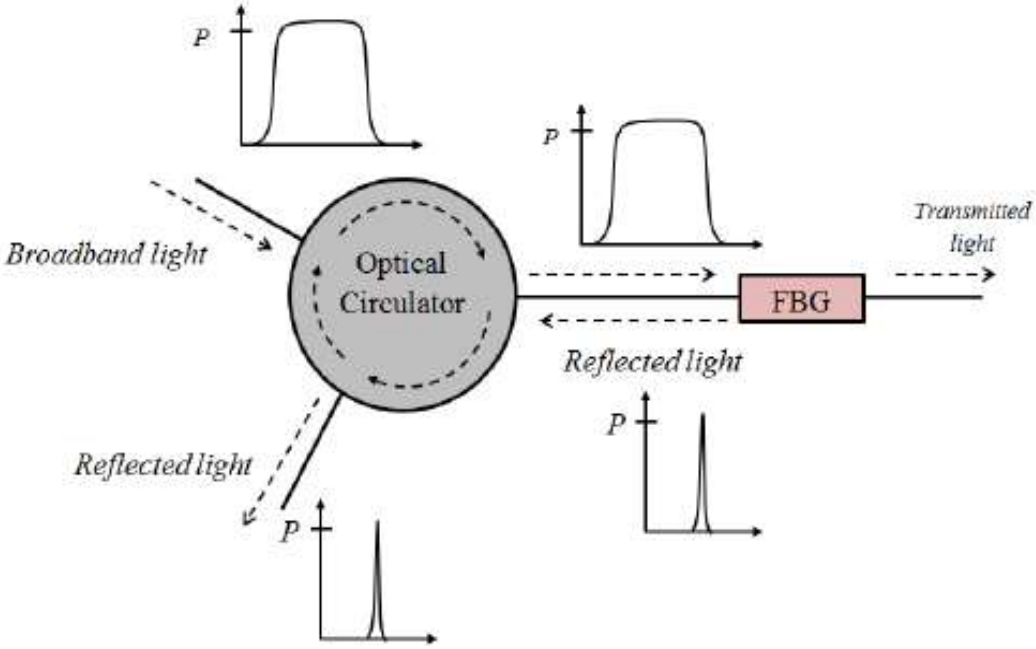


Figure 3. Schematic diagram of the moving light in the circulator-based system by Zohari [36].

4. Experimentation

An FBG was attached to the center of the diaphragm with 3-second glue as shown in Figure 4. The FBG pressure transducer was connected to the pipe leak detection test rig while an air compressor was used to supply pressure as shown in Figure 5.

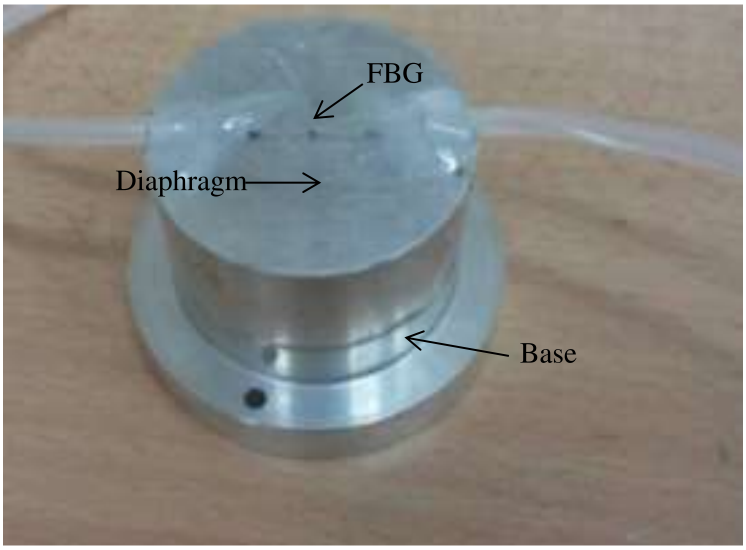


Figure 4. FBG pressure transducer.

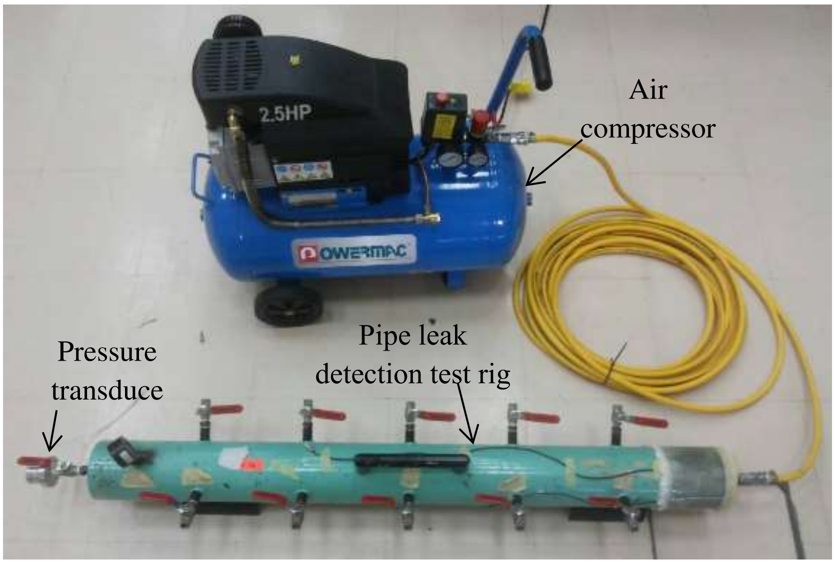
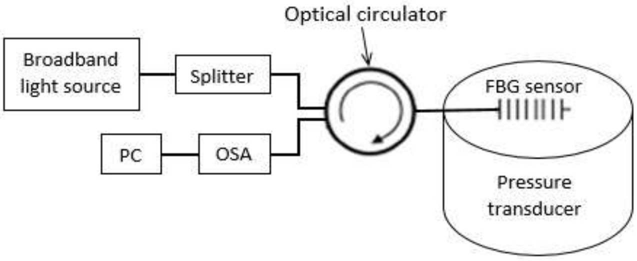


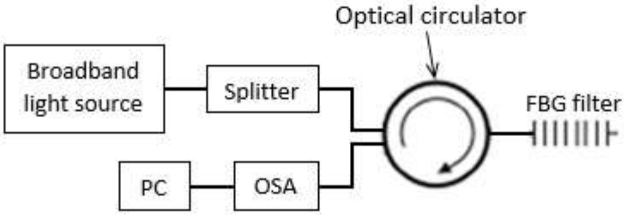
Figure 5. Set up of test rig.

4.1. Bragg wavelength against pressure

The pressure transducer was mounted to the interrogation system as shown in Figure 6; to determine the reflected Bragg wavelength for FBG sensor (set A) and FBG filter (set B). Bayspec (FBGA-F-1525-1565-FP) Optical Spectrum Analyzer (OSA) was used to display the reflected spectrum. The sensitivity of the FBG on pressure sensing was obtained from the relationship between pressure and wavelength shift in FBG sensor. A pressure increment was implemented gradually to get the strain in the FBG sensor through the deformation of the diaphragm.



Set A



Set B

Figure 6. Configuration of interrogation system of set A (top) and set B (bottom).

Observation through OSA shows that there was significant wavelength shift after increasing pressure scheme was applied to the test rig. Once the FBG sensor detected the deformation of the diaphragm caused by the pressure exerted, the grating period changes to a longer or shorter wavelength, therefore causing a shift in Bragg wavelength of the FBG. It can be observed from Figure 7 that the variation of the Bragg wavelength under the increased pressure is linear with pressure applied; and exhibited no considerable variation in the peak power levels. Figure 8 shows the variation of the wavelength of FBG versus pressure. The variation pattern is linear and the slope is 0.278; and the fitting linear correlation coefficient reached 97.29%.

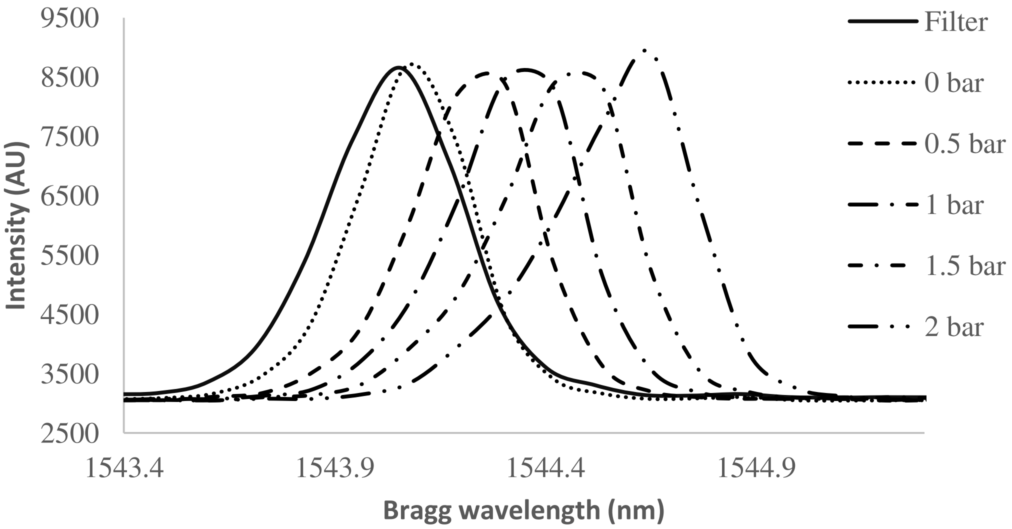


Figure 7. The spectra of Bragg wavelength shift of the sensing FBG at different applied pressure values 0 until 2 bar.

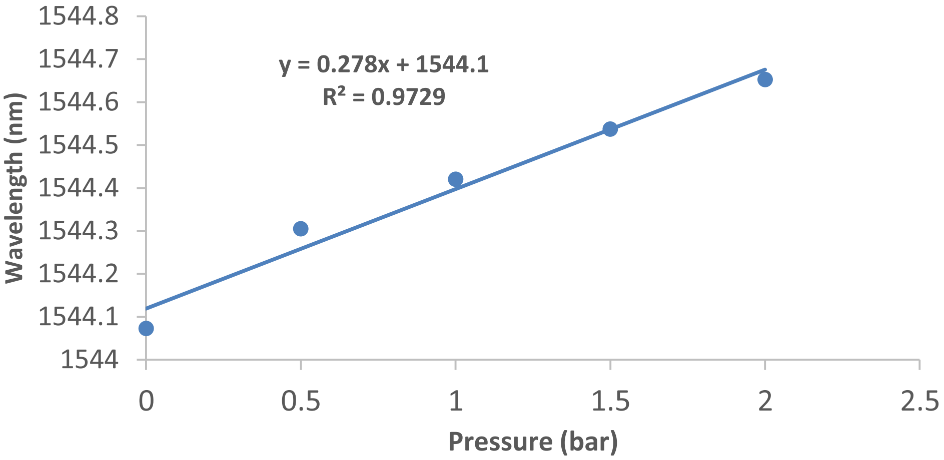


Figure 8. Variation of wavelength of FBG versus pressure.

4.2. Pressure against voltage

For this study, an improved interrogation system was used. Two FBG were used, whereby one of the FBG acts as a sensor and the other as a reference. Figure 9 shows the interrogation system proposed.

Principally, the broadband signal from an (ASE) source is launched into the splitter to emit light through two optical circulators; and to both of the FBGs. The reflected wavelength from FBG sensor will pass through the FBG filter, whereby the matched wavelengths were filtered. Here, the remaining wavelengths were transformed into intensity shift; and converted to voltage readings by photodetector CH1. At the same time, the reflected wavelength from FBG reference will also be converted to the voltage readings by photodetector CH2 as a voltage reference. Note that, FBG reference only detect any intensity variations from the broadband light source.

The normalizing the voltage from FBG sensor with the voltage from FBG reference was done in order to reduce the voltage inconsistency. Voltage reading obtained from different applied pressures setting ranging from 0 to 2 bar within steps of 0.2 bar was recorded. The experiment was repeated for six times to calibrate the pressure transducer before analysis was conducted. All the measurements were monitored utilizing MATLAB real-time graphical user interface (GUI) monitoring system.

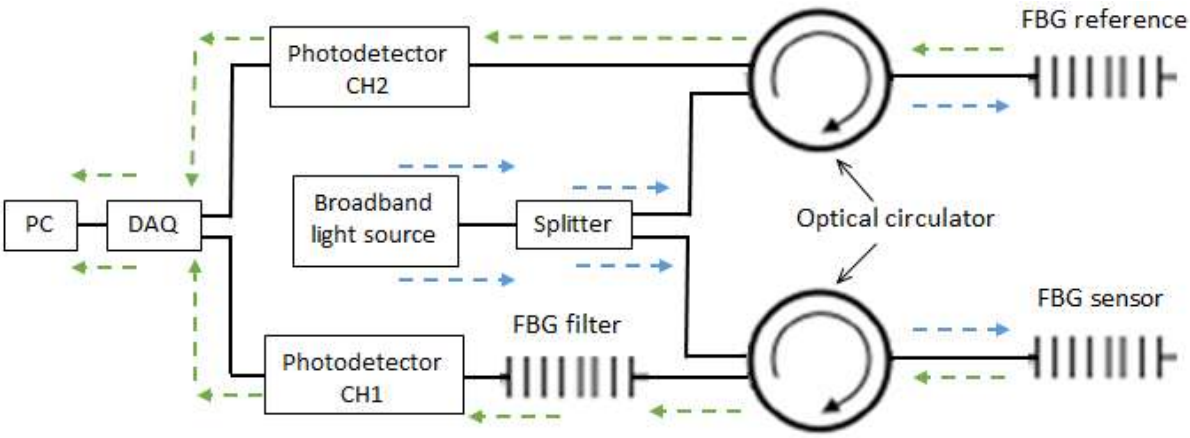


Figure 9. New interrogation system.

The FBG dynamic pressure transducer was connected to the interrogation system as shown in Figure 9 which contains a photodetector to convert the intensity into the voltage. The conversion optical into an electrical signal is aimed in order for the FBG dynamic pressure transducer to be easily connected to an electronic controller or signal processing in software such as DASYLAB and MATLAB via NI (National Instruments) devices. Figure 10 shows the graph of the calibration process. A linear relation was calculated from the averaging of the calibration data and was used in GUI for converting the voltage to the pressure. The linear equation of the calibration process as shown in Figure 11.

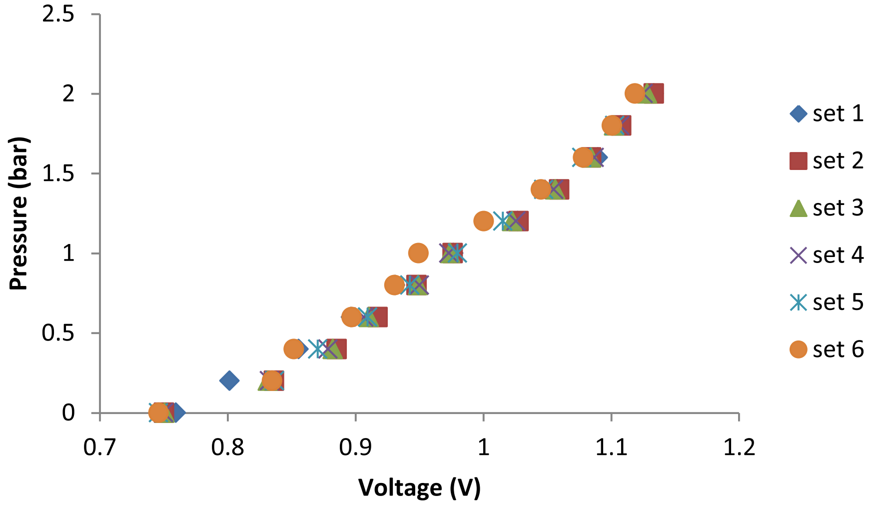


Figure 10. Calibration process.

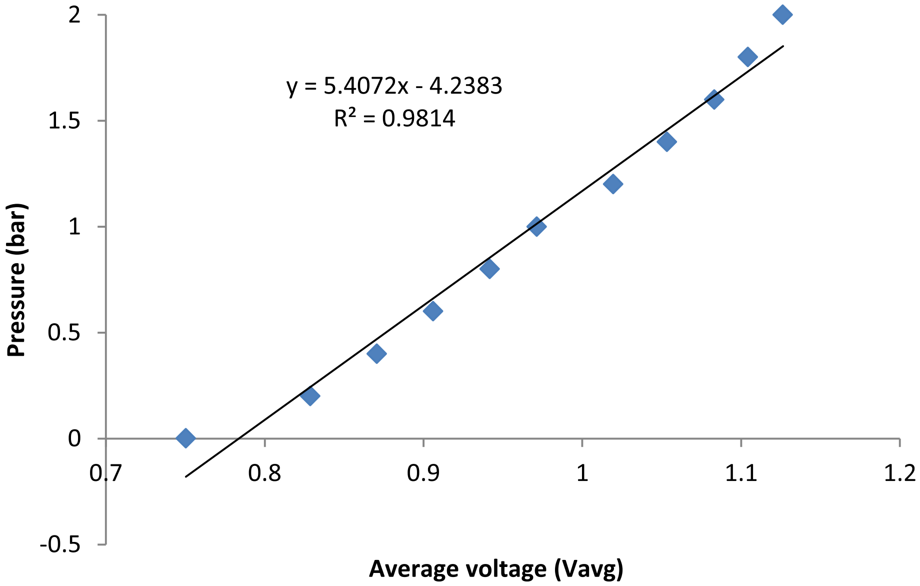


Figure 11. Relationship between pressure and voltage.

4.3. Data validation

A new set of experiment is carried out to find the error of pressure between pressure gauge readings and pressure from FBG pressure transducer readings. 5 samples were recorded as shown in Table 1 below and the errors between two output readings were calculated. Figure 12 shows the data validation between pressure gauge readings and FBG pressure transducer readings. An average error for 5 pressure measurement is found to be 5.348%. From the result, we can conclude that the FBG dynamic pressure transducer has good accuracy and high reliability in measuring pressure.

Table 1. Summarized data of comparison between pressure gauge and FBG pressure transducer.

Sample	**Pressure gauge readings (bar)**	**FBG pressure transducer reading (bar)**	**Error %**
1	0.4	0.350589	12.350
2	0.8	0.764673	4.420
3	1.2	1.14443	4.630
4	1.6	1.5626	2.340
5	2	1.94005	3.000
		Average error	**5.348**

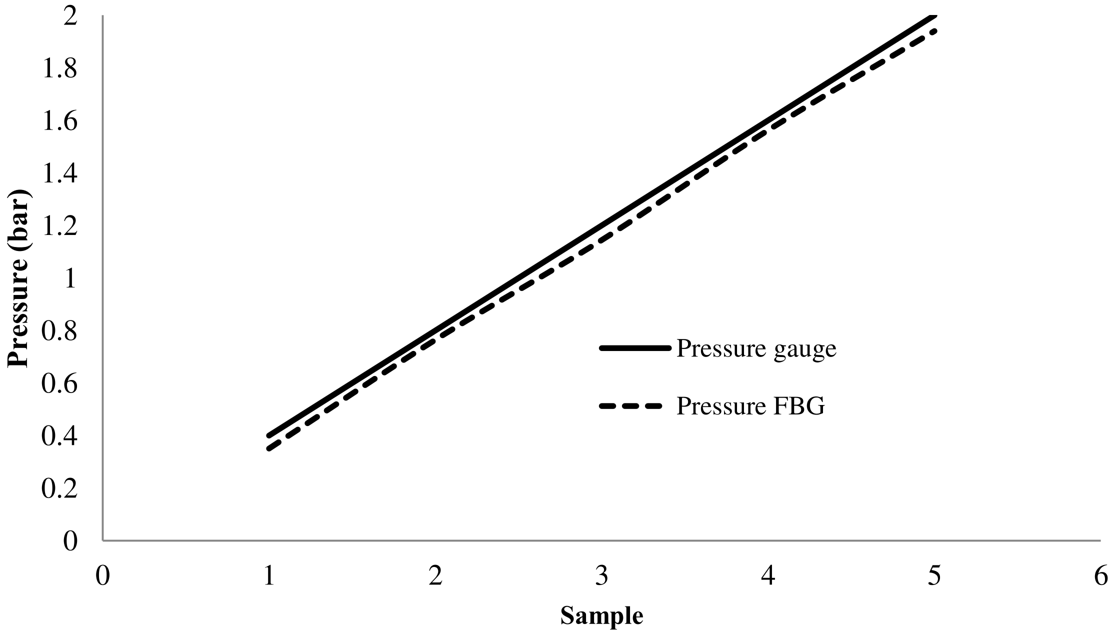


Figure 12. Data validation between pressure gauge and FBG.

5. Conclusions

In this study, new interrogation system was successfully applied to reduce inconsistency voltage. The FBG sensor has a good linearity with a linear correlation coefficient of 97.29% in pressure measurement. From the pressure measurement test between pressure gauge readings and FBG pressure transducer, an average error is found to be 5.348%. Note that, temperature compensation of the pressure transducer has not been taken into consideration as the operating temperature was fixed at room temperature.

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