Strain Monitoring of Pressurized Pipes Using Optical Fiber Bragg Gratings

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Abstract: Strain measurements provide a nondestructive technique for the in-service evaluation and health monitoring of pressurized vessels and pipelines. For these measurements, optical fiber sensors are especially appealing because of their hazard and electromagnetic interference-free nature. Their use also enables the remote operation of the optical sensors, where the sensor electronics and electrical connections are situated away from the sensing sites, which is a major advantage in many situations. These sensors can further be networked by their connecting fibers to achieve unambiguous data read-out of several sensors using reduced wiring and cost-effective installations. In this work, optical fiber Bragg grating sensors are used to measure the hoop strain of pressurized pipes for the purpose of their in-service condition monitoring. The motivation is to make use of the advantages of the optical sensors and investigate their performance characteristics and suitability for pipeline strain monitoring at relatively low operating pressures. Strain measurements using the optical fiber sensor are compared to those obtained using an electrical strain gauge, showing better sensor linearity and simplicity of strain measurement. This comparison justifies the choice to use the optical sensors for the proposed application. The possibility of optical sensors networking using optical fibers along pipelines is also demonstrated.

Keywords: Strain measurements; Pipeline monitoring; Optical fiber sensors; Fiber Bragg gratings.

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رصد انفعال الأنابيب الضغوطة باستخدام محززات براغ في الألياف الضوئية

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ملخص الدراسة: يعد قياس الانفعال من التقوييات غير المتلفة المستعملة لرصد وتقديم حالة الأنابيب والأوعية الضغوطة أثناء تشغيلها. وتعتبر مستشعرات الألياف الضوئية من أهم التقوييات المناسبة لهذه القياسات وذلك لطبيعتها الخالية من مخاطر الانفجار والتفاعل الكهرومغناطيسي، كما أن استخدامها يمكن من تشغيل المستشعرات عن بعد حيث يتم إعداد التوصيلات الكهربائية والأجزاء الإلكترونية عن موقع الاستشعار مما يعد ميزة حيوية في كثير من التطبيقات. ويمكن بالإضافة إلى ذلك تشغيل شبكة من هذه المستشعرات باستخدام الألياف الضوئية لوصول بعضها ببعض مما يخفض من تعقيد التوصيلات وолосات القياسات. يقدم هذا العمل دراسة استخدام محززات براغ في الألياف الضوئية لقياس الانفعال في المحيط الخارجي للأنابيب الضغوطة بغرض رصد وتقييم حالة الأنابيب أثناء تشغيلها. ويفيد ذلك إلى الاستفادة من مميزات مستشعرات الألياف الضوئية ودراسة أدائها ومناسبتها لرصد انفعال الأنابيب تحت تأثير ضغوط تشغيلها المنخفضة نسبياً. وتمت مقارنة قياس الانفعال بهذه المستشعرات الضوئية بقياسه بقياس الانفعال الكهربائي حيث أضحى أن مستشعرات براغ الضوئية أفضل في حساسية وسرعة قياس الانفعال، مما يعني مبولا استخدامها كمستقبلات في التطبيقات المتزعة. كما توضح إمكانية توصيل هذه المستشعرات على طول خطوط الأنابيب باستخدام الألياف الضوئية.

الكلمات المفتاحية: قياس الانفعال؛ رصد حالة خطوط الأنابيب؛ مستشعرات الألياف الضوئية؛ محززات براغ في الألياف الضوئية.

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1. INTRODUCTION

Pressurized pipelines are vital to many commercial and civil ventures. Their damage or failure is very undesirable and their in-service monitoring to avoid the occurrence of such events is an important task (Kishawy & Gabbar, 2010). Fulfilling such a task requires the installation and networking of sensors along the pipelines to continuously check their strain status, which can indicate many abnormal operating conditions of the pipelines, such as overpressure, wall thinning, or pipeline leak, providing possible early warnings for the occurrence of failure events (Morison, Cherpillod, Al-Taie & Mutairi, 2005; Jiang, Ren, Jia, Li & Li, 2017). Different types of sensors have been suggested and investigated for pipeline monitoring, including electrical strain gauges (Atta & Ahmad, 2014), acoustic sensors (Cho, Seo, Jung, Kim & Jung, 2007; Köppe, Bartholmai & Prager, 2012) and optical sensors (Hao, Leng & Wei, 2007; Zhang, Bao, Ozkan, Mohareb, Ravet & Du, 2008; Mishra & Soni, 2011; Ren, Jia, Li & Song, 2014). Several sensor networking techniques have also been proposed, which include wireless networking (Kouche & Hassanein, 2012; Lynch & Loh, 2006) and optical fiber distributed networking (Zhang et al., 2008; Mishra et al., 2011; Rajeev, Kodikara, Chiu & Kuen, 2013). The use of optical fiber sensors for pipeline monitoring is of a special interest as it offers many advantages over other techniques, including a hazard and interference-free operation and the possibility of sensors networking by fibers to achieve unambiguous data read-out from individual sensors (Kleckers, 2009; Sohn, Farrar, Hemez, Shunk, Stinemates, Nadler & Czarnecki, 2004; Mendez, Turner & Costantini, 2013). The use of fiber Bragg grating (FBG) sensors for strain measurements is a well-developed technique which has been adopted in many applications (Rao, 1999). Their use in pipeline strain monitoring is investigated in this project to find out their possible performance advantages that would support their use for in-service pipeline monitoring.

Further to the work previously reported on the use of FBG sensors to evaluate pressurized vessels and pipelines (Hao et al., 2007; Ren et al., 2014; Mendez et al., 2013; Jiang et al., 2017), this study reports on their use to monitor in-service strains occurring at relatively low pressures with emphasis on measurement performance at low strains of the pipelines. The study complements previous work (Hao et al., 2007) on the use of FBG and electrical strain gauges to monitor the damage growth in a fiberglass reinforced plastics pressure vessel. However, it distinguishes itself by providing a more detailed evaluation of the sensors’ performance at low pressures. Moreover, unlike previous studies, such as those cited above, this study compares FBG sensors to electrical strain gauges when used to measure hoop strain in a simple direct attachment to the pipes and examines the complexity of the measurement introduced by the transverse strain coupled to the electrical gauge, which is apparently not significant in the optical fiber sensor. The study investigates the properties of the FBG as a strain sensor by attaching an FBG sensor to a prototype pipe and using an optoelectronic system to enable hoop strain measurements on the pipe during pressurizing stress tests. The results are then compared to those obtained using an electrical strain gauge mounted on the pipe.
during the same tests. The networking of different FBG sensors using optical fibers along pipelines is also examined.

2. THEORY

FBG sensors are made of glass optical fibers with photosensitized cores, where periodic variations in the refractive index of the fiber core waveguide are made using ultra-violet selective exposure of a photosensitized core section forming 1-D Bragg diffraction gratings of a specified periodicity $\Lambda$. The Bragg gratings then induce strong reflections of the light propagating through these fiber sections at selective wavelengths where the Bragg condition for constructive interference of partial reflections holds. The wavelengths at which this condition is satisfied are known as the Bragg (resonant) wavelengths. The first order Bragg wavelength is related to the grating periodicity by the relation (Hill & Meltz, 1997):

$$\lambda_B = 2 n_{\text{eff}} \Lambda$$  \hspace{1cm} (1)

where $\lambda_B$ is the Bragg wavelength in free space and $n_{\text{eff}}$ is the effective refractive index of the optical mode propagating in the fiber core. Any environmental effect that changes the value of $n_{\text{eff}}$ or $\Lambda$ produces a change in the Bragg wavelength, which can be used as a base for sensing. In particular, when the fiber section with the FBG suffers an elongation, the Bragg wavelength is detuned, from which the fiber relative elongation can be measured. In addition to the change in the grating period with fiber elongation due to strain and/or thermal expansion, changes in the optical mode effective refractive index are also induced by strain and temperature variations through the elasto-optic and thermo-optic effects. Thus, both the grating period and the modal refractive index are sensitive to strain and temperature. This correlates both strain and temperature variations to changes in the Bragg wavelength (Haase, 2007). To effectively measure the strain without the interference of temperature variations, either a dual FBG setup or a temperature-compensated single FBG is to be used. Alternatively, strain measurements are to be all done at a constant temperature.

With proper thermal compensation, or under isothermal conditions, the relative detuning in the FBG Bragg wavelength is related to the strain applied on the sensor by the relation:

$$\frac{\Delta\lambda_B}{\lambda_B} = K_o \varepsilon$$  \hspace{1cm} (2)

where $\Delta\lambda_B$ is the change in the Bragg wavelength, $K_o$ is the FBG gauge factor and $\varepsilon$ is the strain coupled to the FBG. A similar relation holds between the relative change in the resistance of an electrical strain gauge and its applied strain:

$$\frac{\Delta R}{R} = K_e \varepsilon$$  \hspace{1cm} (3)

where $\Delta R$ is the change in the strain gauge resistance, $R$, and $K_e$ is its gauge factor, which nominally has a value of 2. The temperature sensitivity of electrical strain gauges to temperature variations is however about an order of magnitude better than that of FBG sensors (Kleckers, 2009).

3. EXPERIMENT AND RESULTS

A prototype Polyvinyl Chloride (PVC) pipe with a 3 mm thick wall, standard dimensional ratio (outside diameter to wall thickness ratio, SDR) of 41 and a length of 1 meter was used for the
experiments. Both ends of the pipe were sealed and an air valve was attached to one side to facilitate pipe pressurizing with compressed air. An FBG was mounted on the outer circumference of the pipe at 20 cm from its center point so as to measure its hoop strain and a 5 mm 120Ω electrical strain gauge (RS Components Ltd.) was similarly mounted on the same distance from the center of the pipe. A photo of the pipe with both sensors attached to it is shown in Figure (1). Air pressure inside the pipe was gradually increased and measured using a mechanical barometer. For the experiments reported here we used unpackaged 10 mm length FBG sensors (3L Technologies, Inc.) and performed the experiments isothermally in a constant temperature air-conditioned laboratory within a relatively short period of time.

The setup used to measure the FBG detuning consists of a super-luminescent light emitting diode (SLED) with a current driver and temperature controller (Superlum Co.), a circulator and an FBG analyzer with software program (BaySpec, Inc.), and a personal computer. A block diagram and a photo of the optical setup are shown in Figure (2). The optical output of the SLED is coupled to the FBG through the circulator, which then directs the light reflected from the FBG to the FBG analyzer for spectral analysis. All optical connections are made using single mode fiber (SMF) cords. The output of the analyzer is electrically coupled to the computer using a universal serial bus (USB) cable for spectrum display and Bragg wavelength determination.

A 5-digits electronic multimeter (Agilent U1272A) was used to measure the resistance of the electrical strain gauge. Five successive readings of the electrical strain gauge resistance and the FBG Bragg wavelength were taken at every pressure value in steps of 10 psi, upon increasing and decreasing of the pressure. The maximum pressure used in this experiment was 100 psi, which is within the safe operating pressure limit of the pipe. The temperature variation during the course of measurement was about ± 1.4°C.

![Figure 1: The pipe used with the strain sensors attached to it.](image1)

The resulting electrical strain gauge relative change in resistance and FBG relative detuning are presented in the graphs of Figure (3). Comparing the graphs of the electrical and optical strain measurements, considering that the strains measured are linearly dependent on the pressure values applied to the pipe, it can be seen that the linearity of the optical sensor output at small values of strain is better than that of the conventional electrical strain gauge.

A series of 5 FBG sensors of Bragg wavelengths separated by 6 nm was then connected to the FBG sensing system with a 5 Km single mode communications fiber to explore the possibility of optical sensors multiplexing using optical fibers along pipelines. The individual reflections of the 5 FBGs mainly followed that of the emission spectrum of the SLED source used.
Based on a simple static analysis of a pressurized long pipe, assuming elastic behavior of the pipe material, the hoop strain is related to the pressure inside the pipe by:

\[ \varepsilon = \frac{P D (2 - \nu)}{4 E t} \]  

(4)

where \( P \) is the increase in pressure inside the pipe, \( D \) is its diameter, \( \nu \) is the material Poisson’s ratio, \( E \) is its Young’s modulus and \( t \) is the pipe wall thickness. For a pipe with given parameters, an increase in the measured hoop strain could thus indicate an increase in its working pressure or a thinning of its wall thickness. The linearity of the strain measurement technique is very important for the proper prediction of either condition.

Assuming the Poisson’s ratio of the pipe PVC material to be 0.41 and its Young’s modulus to be 3 GPa (Professional Plastics, Inc., 2016), the FBG gauge factor obtained from the graph in Figure (3.b) is \( K_0 = 0.68 \), which is within a 13% deviation from the nominal gauge factor of FBG sensors of about 0.78 (Black, Zare, Oblea, Park, Moslehi & Neslen, 2008).

![Figure 2: The optical setup used to measure the fiber Bragg grating wavelength detuning: (A) Block diagram; SLED=Super luminescent light emitting diode, SMF=Single mode fiber, (B) Photo (with the FBG and computer not connected).](image)
This deviation in the calculated value of the gauge factor of the sensor can be due to the actual hoop strain being less than the values calculated theoretically as a result of the short pipe length and end caps effects. This is in addition to any inaccuracy in the values of the material parameters used in the calculation. For a temperature variation of ± 1.4°C, the expected relative detuning in the FBG Bragg wavelength can be calculated to be about ±13x10^{-6} (Haase, 2007), while that due to the strain produced in our experiments for a step of 10 psi is about 250x10^{-6}. Therefore, the effect of temperature variation on the measurements conducted with such coarse pressure steps can be neglected.

For the electrical strain gauge, a direct application of Eq. (3) to the most linear part of the graph in Figure (3.a) (from 70 to 100 psi), considering the calculation of strain based on Eq. (4), would give a value of the gauge factor of about 1.2, which is 40% far from the nominal gauge factor value of 2. This large deviation in the gauge factor could partly be due to the presence of the axial pipe strain acting transverse to the gauge axis, which affects the measurement through the transverse sensitivity of the gauge. A correction of the gauge factor based on the gauge transverse sensitivity coefficient and the ratio of the transverse to axial strains can be obtained using methods described in the literature (Micro-Measurements, 2011). The transverse sensitivity coefficient of the gauge used here was however not available. Expected negative values of the transverse sensitivity coefficient of the gauge would result in smaller actual values of the gauge factor of the sensor. For example, a value of the transverse sensitivity coefficient of the strain gauge of $K_T = -0.5$ would give a value of the gauge factor $K_e = 1.65$, which is closer to the value obtained in our experiments. A direct use of the nominal gauge factor of the electrical sensor of 2.0 would thus lead to a significant underestimation of the values of strain.

Figure 3: The results of pressurizing the PVC pipe: (A) Electrical strain gauge relative change in resistance, (B) Fiber Bragg grating relative detuning.
Apart from the reporting on the use of FBG and electrical strain gauges to monitor the damage in pressure vessels at relatively high pressures (Hao et al., 2007) and a later comparison between the two sensors for dynamic vibration-induced strain measurements (Wang, Huang, Liu & Zhou, 2016), other available contributions do not provide a comparison of the performance of the two sensors at low static strains. Other FBG measurement schemes proposed the use of the FBG sensors in elaborate mechanical sensing arrangements to improve their sensitivity. While these sensing schemes were applied to measure the hoop strain of pipes, they do not provide a comparison of the performance of the FBG and electrical sensors when directly applied to the pipe walls, which we confirm by the experiments reported here to favor FBG sensors especially for low pressure in-service pipe monitoring applications.

4. CONCLUSION

An important task of strain monitoring is the assurance of proper operating conditions, which usually occur at elastic strain values of pipes. This measurement requires good linearity of the strain gauge output at small strain values, which is a feature of the optical fiber Bragg grating confirmed by the work reported here. FBG sensors are also not subjected to a considerable transverse strain sensitivity, which adds more complications to the measurement of electrical strain gauges. Thus, in addition to their other benefits, such as being immune to electromagnetic interference and electrical and fire hazard-free, optical FBG sensors can provide an accurate linear measurement of strains, especially at low strain values, which is very important for the proper prediction of pipeline working conditions. A comparison of FBG sensors to electrical strain gauges for use to measure strain in a simple direct attachment to the pipe wall would then favor FBG sensors for the above reported features. Networking of the optical sensors with optical fibers can further provide a reduction in wiring and offer cost effective installation of the

![Figure 4: The spectrum detected from 5 FBG sensors with different Bragg wavelengths separated by 5 Km of single mode communication fiber.](image-url)
sensing system along the pipelines.

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REFERENCE


