Journal of Natural Gas Science and Engineering 26 (2015) 135–141

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Fiber Bragg grating for pressure monitoring of full composite lightweight epoxy sleeve strengthening system for submarine pipeline

N.F. Razali [a, 1], M.H. Abu Bakar [a, *, 1], N. Tamchek [b], M.H. Yaacob [a, 1], A.A. Latif [b], K. Zakaria [c], M.A. Mahdi [a, 1]

[a] *Wireless and Photonics Network Research Center, Faculty of Engineering, University Putra Malaysia, 43400, UPM, Serdang, Malaysia*
[b] *Department of Physics, University Putra Malaysia, 43400, UPM, Serdang, Malaysia*
[c] *Merit Technologies Sdn Bhd, Sunway Damansara Technology Park, Selangor, Malaysia*

A R T I C L E I N F O

Article history:
Received 11 February 2015
Received in revised form
1 June 2015
Accepted 2 June 2015
Available online 19 June 2015

Keywords:
Fiber Bragg grating
Strain
Pipeline
Optical sensor

A B S T R A C T

This work investigates the use of fiber Bragg grating (FBG) for monitoring of pressure in a full composite lightweight epoxy sleeve strengthening system for offshore oil and gas pipeline. An FBG incorporated within the polyethylene sleeve served as an indicator of increasing pressure and displacement inside the pipeline. The wavelength shift of the FBG increased linearly with the increment of pressure and displacement, producing measured sensitivity of up to 0.8831 nm/kN and 0.902 nm/mm, respectively. The effect of temperature on the embedded sensor was also analyzed and it was found that the temperature sensitivity of the sensor below 55 °C was only 9.04 pm/°C. The excellent pressure sensitivity and its minimal susceptibility to temperature further accentuate the potential of fiber-based sensor as an effective and accurate alternative for pipeline integrity monitoring.

1. Introduction

Petroleum pipeline is an integral infrastructure in transporting crude oil and gas, which is among the most important mineral resources contributing to world advancement and economy. In harsh marine environment, petroleum pipeline could be affected by landslide, earthquakes and corrosion, which increase the risk of leakage in the pipeline. Pipeline reinforcement method using metal clamps was introduced to address this issue and lengthen the lifetime of compromised pipeline but this approach itself is saddled with problems such as vulnerability to corrosion and cumbersome weight (Shamsuddoha et al., 2013). A lightweight and equally effective alternative is the full composite Helicoid Epoxy Sleeve (Fig. 1), which is a pipeline strengthening system composed of a carbon fiber (CF) reinforced, mechanically interlocking Polyethylene (PE) strip that is helically wound around the pipe, thus allowing an annulus around the pipe to be filled with epoxy grout (De Jong, 2013).

The Helicoid system however, lacks an integrity-monitoring sensor, which could allow a faster, real-time assessment of its current condition. As of yet, no sensor has been deployed specifically for pipeline reinforcement method. For pipeline leakage detection, several methods have been proposed such as pigging, fuzzy logic system, pressure transient monitoring and wireless sensor (Davoudi et al., 2014; da Silva et al., 2005; Misiunas et al., 2005; Stoianov et al., 2007). Although widely chosen for integrity assessment application, pigging lacks continuous monitoring capability, which exposes pipelines to possible failure in between the periodical checks (Davoudi et al., 2014). Consistent monitoring accorded by (da Silva et al., 2005; Misiunas et al., 2005; Stoianov et al., 2007) is highly preferred but the methods are less suitable for submarine applications due to issues with underwater operation. Fiber optic sensor has gained a lot of interest due to several clear advantages such as simplicity, compact-size, and insensitivity to electromagnetic interferences (Hill and Meltz, 1997). In fact, the use of optical fiber Bragg Grating (FBG) for pipeline leakage detection has been investigated and it was found to be a feasible approach (Tanimola and Hill, 2009; Hassan et al., 2011). Moreover, fiber optic sensors are passive sensors that do not require individual power supply to operate. Combine that with low fiber attenuation,

* Corresponding author.
E-mail addresses: mhab@ieee.org (M.H. Abu Bakar), nizamtm@gmail.com (N. Tamchek), info@merit.net.com.my (K. Zakaria).
[1] wipnet@eng.upm.edu.my.

http://dx.doi.org/10.1016/j.jngse.2015.06.020
1875-5100/

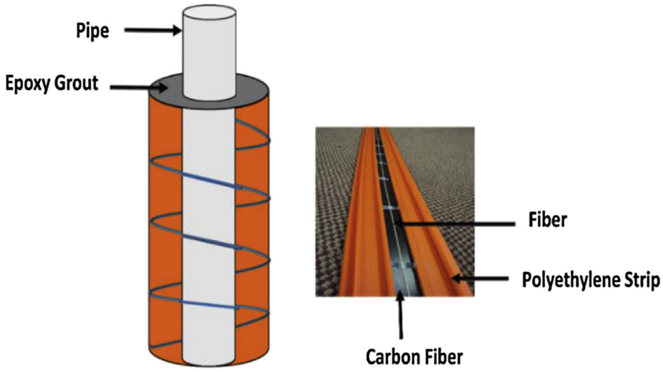

Fig. 1. Pipeline using helicoid epoxy sleeve.

the optical approach can be deployed for pressure monitoring in long-distance remote sensing configuration (Tanimola and Hill, 2009).

However, the proposed system in Tanimola and Hill (2009) is highly unsuitable for submarine pipeline, as the detection would only occur once the fluid is released into the atmosphere, which would be an environmental catastrophic underwater. The method in Hassan et al. (2011) is safer in comparison but would require a separate installation process exclusively for the sensors. Therefore in this work, we explore the potential of using FBG as a sensor to continuously monitor the pressure in Helicoid Epoxy Sleeve system. This collaborative research with the proprietary owner of Helicoid (Merit Technologies Sdn Bhd) aims to eventually produce a complete commercial solution consisting of the Helicoid Epoxy Sleeve and the pressure monitoring system. The current study focuses on characterization of the FBG prior to its embedment within the prepared Helicoid Epoxy Sleeve up to the final load and temperature testing of the sample. The output shows excellent strain and pressure measuring capability of the embedded FBG sensor with minimal temperature sensitivity.

2. Sensing principle

When a broadband source interacts with the gratings of an FBG, a narrowband spectral output known as the Bragg wavelength is reflected by the well-known formula (Werneck et al., 2013):

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

The Bragg wavelength (λ_B) depends on the effective refractive index (n_{eff}) of the fiber and the periodicity of the grating (λ), which can be affected by temperature and strain. Thermal expansion causes the effective refractive index and the spacing of the gratings to change simultaneously; ultimately shifting the Bragg wavelength. This fractional Bragg wavelength shift for temperature change ΔT can be written as (Wang et al., 2013):

$$\Delta\lambda_B/\lambda_O = (\alpha + \zeta)\Delta T \tag{2}$$

Where α is thermal coefficient for the fiber. The quantity ζ represent the thermo-optic coefficient. Therefore, the strain effect on an optical fiber for a constant temperature environment can be expressed as (Wang et al., 2013):

$$\Delta\lambda_B/\lambda_O = (1 - p_e)\varepsilon \tag{3}$$

Where the $\Delta\lambda_B$ is wavelength difference compared to the original Bragg wavelength, λ_O, the p_e is gage factor and ε is the strain applied on optical fiber. To characterize the strain coefficient of the FBG, an experimental setup is proposed as illustrated in Fig. 2.

The telecommunication-standard bare FBG with center wavelength of 1550.61 nm was gripped at both ends using two vacuum-assisted clamps placed on top of the Vytran GPX-3000 series fiber processing workstation stages. The stages can be moved at a resolution of 0.001 mm. The fiber was stretched from its idle position by moving the motor of the left-hand stage away from the right-hand stage while the removal of strain was conducted simply by bringing the left-hand stage back to its initial position. For this measurement, the displacement is fixed to only 0.04 mm to avoid from optical fiber breakage but sufficient to characterize the optical fiber strain coefficient. Continuous monitoring of the wavelength shift was performed in a constant room temperature environment throughout the experimental process to avoid perturbations coming from temperature changes.

Fig. 3 shows plot of the wavelength shift including the hysteresis loop of the graph of wavelength shifts versus the strain. Hysteresis is observed due to viscoelastic material used, where the rate of energy absorbed during loading is lower than the rate of energy released during unloading (Abang and Webb, 2013). This is a common occurrence in viscoelastic materials leading to the observation of dissimilar path between the loading and unloading curves. In viscoelastic material, the relationship between stress and strain is dependent on time (Liu et al., 2005). As a result, phase difference exists between the stress input and the strain response of the fiber sensor. The effective stiffness of the fiber depends on the rate of strain applied onto the fiber. When the stage is unloaded (returned to its original position), the strain does not decrease in proportion to the stress as there is a phase delay between the two responses. Due to this phase lag, the dissipation of mechanical energy is affected thus causing hysteresis (Lakes, 1998). The strain coefficient of the optical fiber during loading process is 251.88 nm/με, while the unloading process produces higher strain coefficient, which is 297.73 nm/με.

3. Epoxy sleeve sample preparation

The Epoxy sleeve was characterized prior to embedment of the FBG sensor. As shown in Fig. 4, the sleeve is basically composed of a PE strip as the outer layer, followed by protective CF strip. A layer of epoxy grout then forms the inner layer of the Helicoid system. The epoxy grout is an excellent adhesive while the PE strip is a chemically resistant plastic material that is specifically designed for the Helicoid system for further protection again harsh environment conditions. The employment of advanced materials such as carbon fiber further increases the effectiveness of the pipeline reinforcement system.

For the purpose of this work, the sample of epoxy grout measuring 270 mm long × 25 mm high × 25 mm width was fabricated based on ASTM C 580 standard (ASTM C580-02, 2012). The epoxy resin was stirred in a beaker at low speed to avoid air

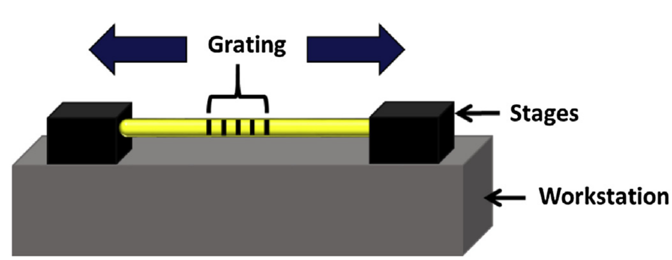

Fig. 2. Experiment setup for strain sensing.