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Investigation of Positioning of FBG Sensors for Smart Monitoring of Oil and Gas Subsea Structures

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***Abstract*—Condition monitoring of offshore structures is an indispensable task in the oil and gas industry. Fibre Bragg Grating (FBG) is the key technology used down-hole in order to sense different physical parameters such as strain, vibration, etc. This paper investigates the effect of FBG sensor positions on its reflected signal, in order to optimise the sensor positioning plan in structural health monitoring of subsea structures. Theoretical and experimental study was carried out on FBG sensors, to evaluate its strain sensitivities with varying positions. In addition, micro-displacement based strain analysis of FBG was carried out using a cantilever setup, in order to identify the effects of tensile and compressive strain under various load conditions. Furthermore, the effect of different grating parameters on FBG sensing signal were also analyzed. Theoretical modeling and simulation of FBG was conducted in MATLAB using the coupled mode theory.**

Keywords*— *fibre optic sensors; FBG; coupled mode theory; structural health monitoring.

I. INTRODUCTION

Structural health and condition monitoring, where advanced sensing technologies are employed, is a vital element in offshore oil and gas sector. It plays a crucial role in ensuring safe and efficient explorations in order to significantly enhance the productivity from ultra-deep oil fields. Currently, most of the subsea assets have almost reached their design lifetime, though considerable amount of untapped hydrocarbon reserves are still available. Consequently, structural integrity and maintenance of the deteriorated subsea structures has become very important considering its impact on the environment and oil and gas economy as a whole. Hence, in order to extend the life span of valuable subsea assets, there is an urgent need for improved and reliable condition monitoring systems for its infrastructures, with increased signal transmission length and enhanced spatial coverage to retrieve sensing data from deeper zones.

Fibre optic sensing technology offer immense possibilities for real time and remote monitoring of oil and gas well bore structures. Unlike the traditional electrical sensors, they have many inherent advantages such as long reach, immunity to radio frequency and electromagnetic interference (EMI), ability to operate in harsh environmental conditions, corrosion resistance, etc. A single fibre optic cable serves both as the sensing element as well as the data transmission system. Considering different fibre optic sensing technologies available, FBG (Fibre Bragg Grating) is the only technology which can sense almost all types of physical parameters and also offers sensing at multiple points simultaneously. Another unique characteristics of FBG is wavelength encoded measurements and hence no information is susceptible to light power fluctuations [1]. However, precise placement and alignment of FBG sensor is a key requirement in sensor integration for accurate measurement, prior to securing them to the well bore structures [2]. Identifying the right position of FBG sensors with respect to pipeline axis is very important because the FBG sensors shows highest sensitivity and records peak intensity at specific points [3]. This aids in the precise and accurate measurements of the physical parameters in long distance remote monitoring applications.

II. THEORY

The fundamental principle of FBG sensor depends on the Bragg condition which states that any changes in physical parameters such as pressure, temperature, strain etc modifies the refractive index or grating period of the fibre grating, which in turn changes the Bragg reflected wavelength correspondingly [4].

The Bragg reflected wavelength [5] is given by:

$$\lambda_b = 2.n_{eff}.\Lambda \tag{1}$$

Where n_{eff} is the effective refractive index and Λ is the period of the grating or spatial period.

A. *Modeling of FBG using Coupled Mode Theory*

FBG modeling and characterization were carried out by solving the coupled mode equations using the transfer matrix method [6].

The power reflection coefficient, R [5] is given by:

$$R = \frac{sinh^2(\sqrt{k^2 - \hat{\sigma}^2}L)}{cosh^2\left(\sqrt{k^2 - \hat{\sigma}^2}L\right) - \frac{\hat{\sigma}^2}{k^2}} \tag{2}$$

Where, L is the grating length.

k is the AC (Associated Coupling) coefficient [5] and is given by: (3)

$$k = \frac{\pi}{\lambda}.\delta n_{eff}.v$$

v is the fringe visibility.

σ is the DC (Demi Coupling) coefficient [5] and is given by:

$$\sigma = \frac{2\pi}{\lambda}.\delta n_{eff} \tag{4}$$

δ is the tuning parameter and is given by: (5)

$$\delta = 2\pi.n_{eff}\left[\frac{1}{\lambda} - \frac{1}{\lambda_d}\right]$$

$$\hat{\sigma} = \delta + \sigma \tag{6}$$

λ_d is the design wavelength or centre wavelength.

B. *Strain Sensitivity of FBG*

Fractional change in Bragg wavelength [7] for applied strain $\left(\varepsilon = \frac{\Delta\Lambda}{\Lambda}\right)$ is given by:

$$\frac{\Delta\lambda_b(\varepsilon)}{\lambda_b} = (1 - \rho_e)\Delta\varepsilon \tag{7}$$

Where ρ_e is the photo-elastic coefficient and $\Delta\varepsilon$ is the variation in strain value.

III. RESULTS AND DISCUSSIONS

A. *FBG Modeling*

Modeling of FBG was done based on coupled mode theory, which describes the grating spectra of a uniform FBG. According to couple mode theory, the incident wave gets coupled to the same counter propagating wave and thus it gets reflected as the Bragg reflected signal. Theoretical modeling of FBG performed in MATLAB, helped in understanding the effects of different grating parameters and their effects on optical pulse properties like amplitude and spectral width.

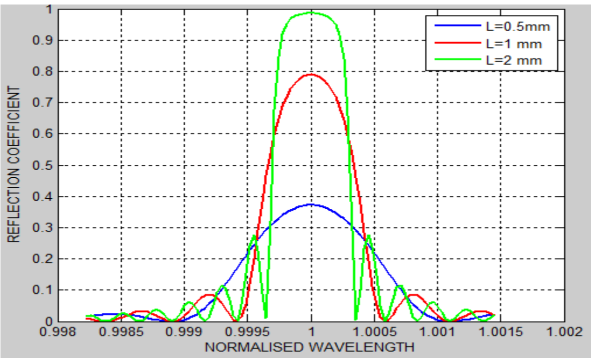

Fig. 1. Reflectivity curve of FBG with different grating lengths

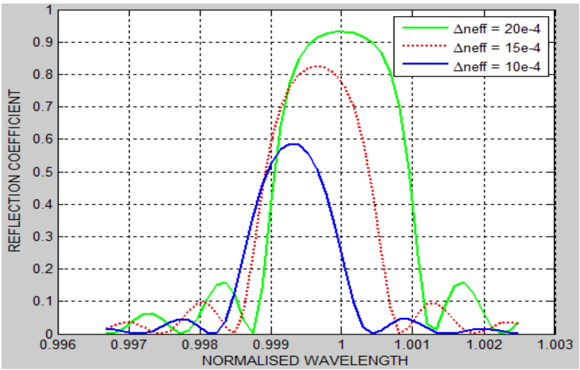

Fig. 2. Reflectivity curve of FBG with different refractive index change

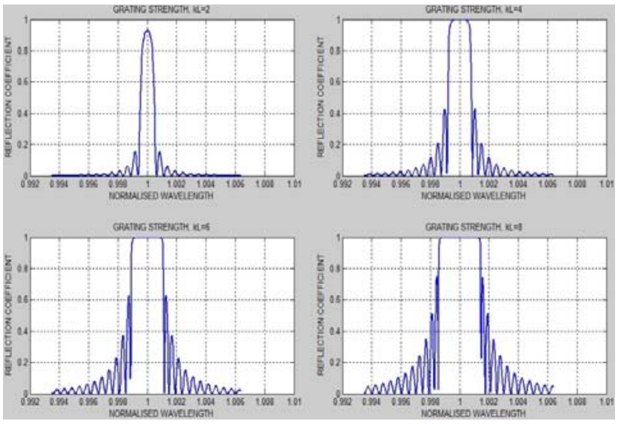

Fig. 3. Reflectivity curve of FBG with different grating strengths (kL = 2,4,6 and 8 ; Δ*neff* = 10^{-4}; L= 1mm)

Fig. 1, 2 and 3 shows the power reflectivity curves for uniform gratings plotted against normalized wavelength (λ/λ_{max}) with varying grating parameters such as grating length (L), effective refractive index (n_{eff}) and grating strength (kL). The design wavelength is taken as 1550 nm and n_{eff} is taken as 1.45.

From Fig. 1 and 2, it is obvious that the reflection coefficient increases with increase in refractive index change and grating length. Also from Fig. 3 we can observe that with decrease in grating strength (kL), the bandwidth also gets reduced. When the number of grating periods, $N = L/\Lambda$ is larger or smaller, the reflection coefficient and width would be narrower or broader, respectively, for a given value of kL [5].

Simulation results have shown that the grating parameters have significant effects on the amplitude and spectral width of the FBG reflected signal. Therefore, by properly optimising these grating parameters, a sharp reflection signal can be obtained from the FBG sensor. Moreover, considering the finite optical spectrum, in order to accommodate more FBG sensors down-hole, spectral width of FBG reflected signals have to be reduced. Furthermore, reduction in reflected signal bandwidth minimizes crosstalk and thereby the cross-sensitivity issues of FBG to some extent. Hence, fine tuning of fibre grating parameters enhances FBG sensor capability by improving its sensing range, accuracy and the number of sensors that can be employed within the oil well bore.

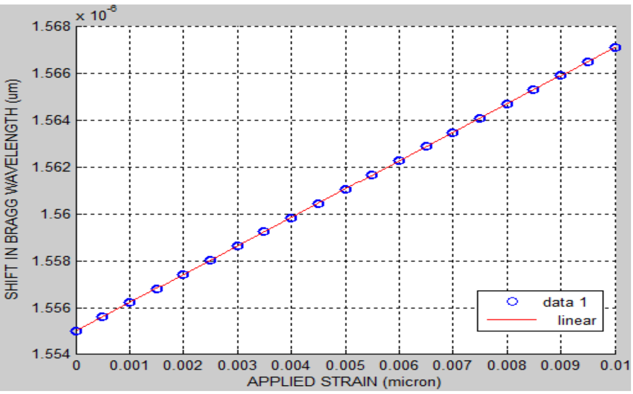

Fig. 4. FBG strain sensitivity graph

Fig. 4 shows the FBG strain sensitivity graph, which is the plot of shift in Bragg wavelength and change in applied strain. FBG strain sensitivity factor calculated theoretically varies linearly with applied strain. The strain sensitivity of FBG occurs mainly due to the compression and expansion of its grating period and also the strain-optic effect; which is defined as the strain-induced change in glass refractive index [8]. For experimental evaluation of FBG strain sensitivity, cantilever vertical displacement due to load is considered, which is again directly proportional to applied strain.

B. *FBG Experimental Results*

Experiments were carried out using high wavelength resolution, high dynamic range instruments like Optical Spectrum Analyzers (OSAs) and broad band light sources, in order to characterize the optical properties of FBGs. Optical spectrum gives information about the features of the grating and also the shift in wavelength with changes in physical parameters. White light source from Ando (AQ-4303B) was coupled to the FBGs using a 50:50 coupler and the reflected signal from FBGs were detected and analyzed in the Anritsu OSA (MS9710C).

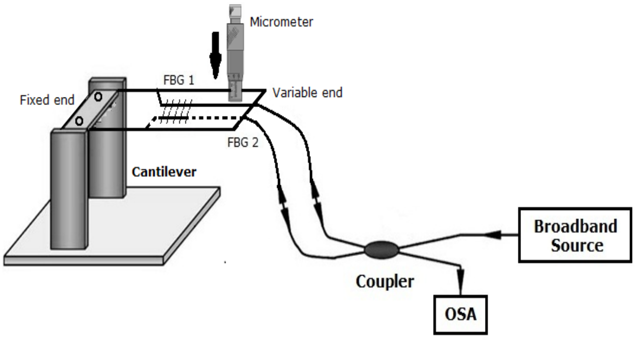

Fig. 5. Pictorial view of FBG strain analysis experimental setup

Fig. 5 shows the pictorial view of the cantilever setup used to carry out the micro-displacement based compressive and tensile strain analysis. In order to analyse both types of strains a dual FBG sensor configuration was used. Two FBGs with reflectivity wavelength 1555 nm and 1540 nm were glued on to the cantilever metal plate with, one above and one below the cantilever respectively. The cantilever plate was made of Aluminium material with dimensions of 30cm x 3cm x 0.3 cm. One end of the cantilever was fixed and to the other end strain was applied by a micrometer which is fixed on to a translational stage. The micrometer was varied in steps of 0.05 mm in order to take the readings.

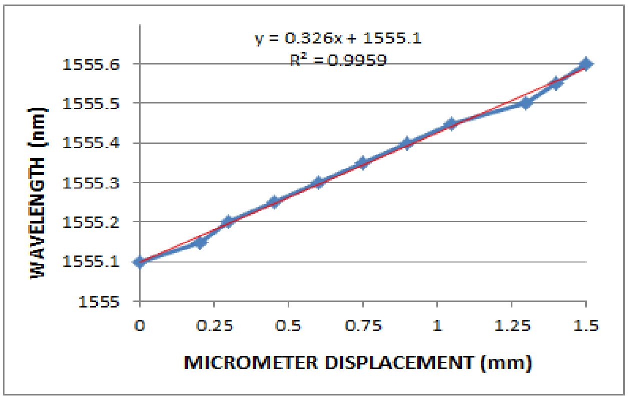

Fig. 6. Wavelength vs Displacement on application of tensile strain

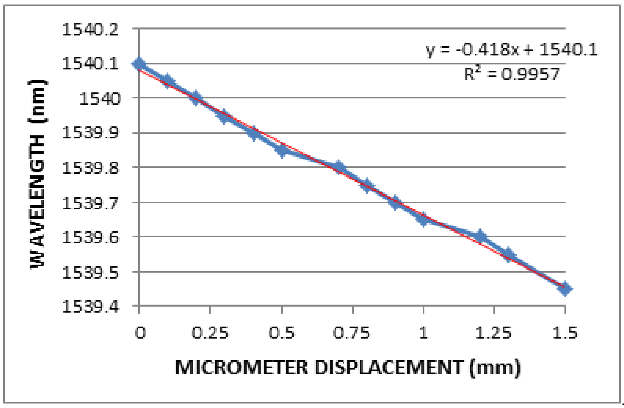

Fig. 7. Wavelength vs displacement on application of compressive strain

From Fig. 6 and 7, the FBG reflected wavelength linearly increases with tensile strain and linearly decreases with compressive strain. The reflectivity curve of the FBGs experiences an upward and downward wavelength shift on application of the micrometer displacement for tensile and compressive strain respectively. The strain measurements were taken under constant temperature conditions, in order to avoid errors due to temperature coupling.

Further analysis was carried out by varying the positions of strain application on the cantilever plate. Strain was applied at 4 different positions, each at a distance of 7.5 cm from each other. Fig. 8 illustrates the different positions on the cantilever were strain was applied using the micrometer.

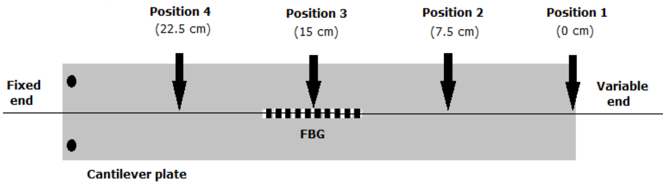

Fig. 8. Illustration of cantilever positions 1-4

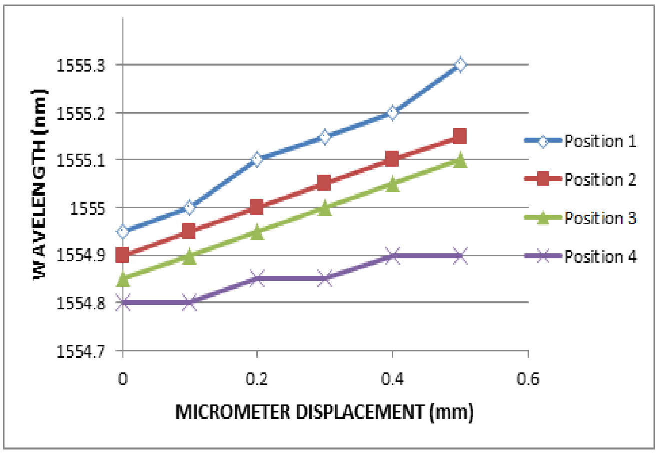

Fig. 9. FBG Tensile strain responses at different cantilever positions

From the graph shown in Fig. 9, it is clear that the FBG reflected wavelength graph shifts downwards with increasing distance from the cantilever free end, maintaining the linear trend. The FBG sensors showed peak strain sensitivities at specific positions and also the reflected wavelength response experiences a shift with changing positions of strain application. Hence, it is obvious that FBG responds differently to changing strain positions. This response of FBGs can be utilised in condition and health monitoring of offshore buried pipelines and other subsea structures.

IV. CONCLUSION

The investigations carried out on FBG sensors identified the relevance of proper positioning of FBG sensors for condition monitoring of offshore structures. A properly positioned FBG experiences an enhancement in its sensitivity. The experimental study conducted using the cantilever set-up helped in identifying the changing response of FBG with different types of strain application (compressive and tensile strain) and also with varying strain positions. MATLAB simulations conducted on FBG sensor revealed the possibility of optimising its grating parameters to achieve higher accuracy, improved sensing range and increased number of sensors down-hole by tuning its reflectivity and spectral width. To sum up, identifying the right position of FBG sensors with respect to pipeline axis and other subsea infrastructures and optimisation of its various grating parameter enhances its capabilities for structural health monitoring, as FBG sensors records highest amplitude and peak sensitivity at specific points. Optimised positioning of FBG sensors aids in precise and accurate measurement of physical parameters and also improves the sensor range within ultra-deep oil well. These improved capabilities of FBG sensors make it the best possible replacement for existing down-hole electrical sensors.

References

[1] Lee B. Review of the present status of optical fiber sensors. *Optical Fiber Technology.* 2003; 9(2):57-79.

[2] Inaudi D, Glisic B. Long-range pipeline monitoring by distributed fiber optic sensing. *Journal of pressure vessel technology.* 2010; 132(1):011701.

[3] Habel WR, Schukar V and Hofmann D. Requirements to Establish Fibre-Optic Sensors for Monitoring of Structures. *EWSHM-7th European Workshop on Structural Health Monitoring*; 2014.

[4] Hill KO, Meltz G. Fiber Bragg grating technology fundamentals and overview. *Lightwave Technology, Journal of.* 1997; 15(8):1263-1276.

[5] Erdogan T. Fiber grating spectra. *Lightwave Technology, Journal of.* 1997; 15(8):1277-1294.

[6] Kashyap R. *Fiber bragg gratings.* : Academic press; 1999.

[7] Othonos A. Fiber bragg gratings. *Review of scientific instruments.* 1997; 68(12):4309-4341.

[8] Mihailov SJ. Fiber Bragg Grating Sensors for Harsh Environments. 2012; Sensors 2012(12):1898-1918.