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A buoyancy-based fiber Bragg grating tilt sensor

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ABSTRACT

In this paper, a novel design of fiber Bragg grating tilt sensor is proposed. This tilt sensor exhibits high angle sensitivity and resolution. The presented tilt sensor works on the principle of the force of buoyancy in a liquid. It has certain advantages over the other designs of tilt sensors. The temperature effect can be easily compensated by using an un-bonded or free FBG. An analytical model is established which correlates the Bragg wavelength (λ_B) with the angle of inclination. This model is then validated by the experiment, where the experimental and analytical results are found in good agreement with each other.

Key Words: Fiber Bragg grating (FBG), Tilt sensor, Inclinometer etc.

1. INTRODUCTION

Fiber Bragg grating (FBG) sensors are one of the most preferable sensors in the field of structural health monitoring (SHM). Unlike the traditional sensors, the FBG sensors are known for their high accuracy, immunity to electromagnetic interference (EMI), multiplexing capability, small diameter etc. [1-3]. The geotechnical engineering community has been showing a lot of interest in FBG sensors. The FBG sensors have been used to monitor various parameters related to geotechnical structures such as strain, vibration, vertical/lateral deflection etc. [5-6].

In the construction industry, it is very important to monitor the movement of soil. The soil moves because of the heavy construction activities such as deep excavation for subway tunnels, underpasses etc. in the nearby area. The soil movement can be monitored using tilt sensors or inclinometers. Various types of tilt sensors have been developed and reported in the literature. The fiber Bragg grating (FBG) based tilt sensors are highly accurate and sensitive. The tilt sensors measure the angular deflection of an object from a reference plane [7]. A novel two-dimensional temperature-insensitive tilt sensor employing FBG sensors was demonstrated. The FBGs were glued to a cylindrical cantilever and a weight or a body is attached to the other end of the cantilever. The inclination/tilt induces bending in the cantilever which in turn changes the Bragg wavelength of the FBGs. The tilt accuracy and resolution are $\pm 0.2^o$ and 0.013^o respectively [8]. The measurement range for the proposed tilt sensor is $\pm 40^o$. With a similar approach, a one-dimensional tilt sensor was proposed with a rectangular cantilever [9]. Two FBG sensors were bonded to the opposite sides of the cantilever beam, making the tilt sensor temperature independent. The resolution and range of such cantilever based tilt sensors are reasonably good, however, their performance largely depends on the bonding material which is used to bond FBG on the cantilever. For a long term application, the performance of the bonding material degrades significantly in a hostile environment. In a different FBG based tilt sensor design, four FBGs were integrated into a simple configuration. In this configuration, a weight (or body) was hung to a circular plate through equally long fibers on which FBG were inscribed [7]. The weight of the body redistributes itself among all the four FBGs if the angle of inclination is changed. This presents a relatively complex configuration of an FBG based tilt sensor.

Further, a different design of tilt sensor was presented which is free from any mechanical joint or bonding. It is capable of measuring the magnitude as well as the direction of inclination [10]. The resolution and the measurement range are good enough for geotechnical applications; however, the design is complex and fragile. A novel design of

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tilt sensor employing an FBG inscribed on a special fiber called polarization-maintaining (PM) fiber was also presented. It is an intensity based temperature insensitive tilt sensor design [11]. The measurement range is good but the resolution and the repeatability are not good enough. A chemically etched FBG was also used in a fiber-optic inclinometer. The chemically etched fiber Bragg grating was connected to a hollow-core fiber (HCF) filled with tin, which functioned as a pendulum. The inclination induced bending in the FBG and therefore, the reflection characteristics of the FBG changed. However, the stability and repeatability of this sensor need further investigation. During the installation process, the tilt sensor might get some rotation which affects the performance of the tilt sensor. None of the tilt sensor available in the literature is able to avoid this effect.

In this paper, a novel design of buoyancy-based FBG tilt sensor is proposed. Unlike other FBG inclinometer designs, this design consists of an un-bonded FBG; therefore its performance is independent of mechanical bonding or mechanical joint. In this design, the FBG fiber is immersed into the water, hence its performance is not likely to be affected by mechanical or structural vibrations exhibiting higher stability. Also, a design of tilt sensor is presented whose response is independent of rotation which might happen during the installation process.

2. THEORY

2.1 FBG and its principle

In FBG sensors, grating (periodic refractive index profile) is inscribed into the core of the fiber as shown in the Fig.1. An Excimer laser (248 nm) and phase masks are used to inscribe the grating. When the broadband light passes through a grating, a particular wavelength is reflected back. This wavelength is called Bragg wavelength (λ_B) and is given as [13]

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

Where n_{eff} is the effective refractive index of the core of the fiber and Λ is the grating period (the distance between the consecutive grooves of the grating) of the FBG. The Bragg wavelength changes linearly with the change in strain (ε) or the change in temperature as shown in Fig. 1. The strain in terms of change in the Bragg wavelength is given by

$$\varepsilon = \frac{\Delta\lambda_B}{\alpha} \tag{2}$$

Where $\Delta\lambda_B$ is the change in the Bragg wavelength and α is the wavelength-strain sensitive factor.

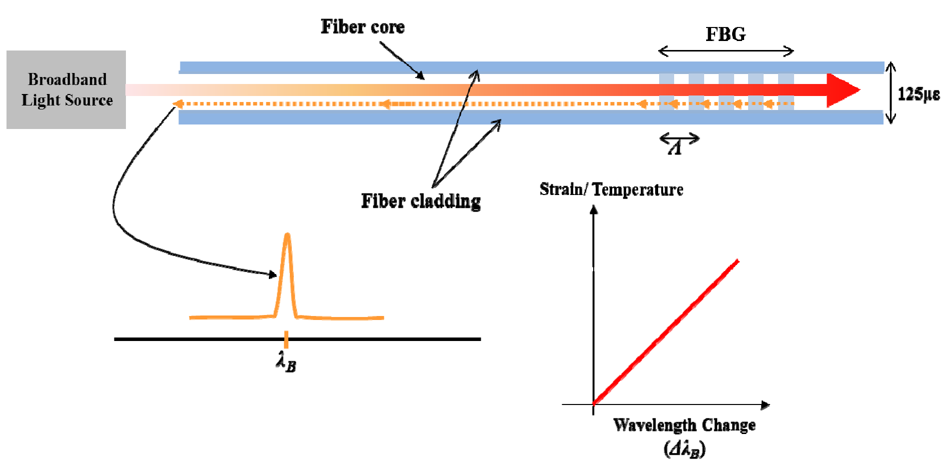
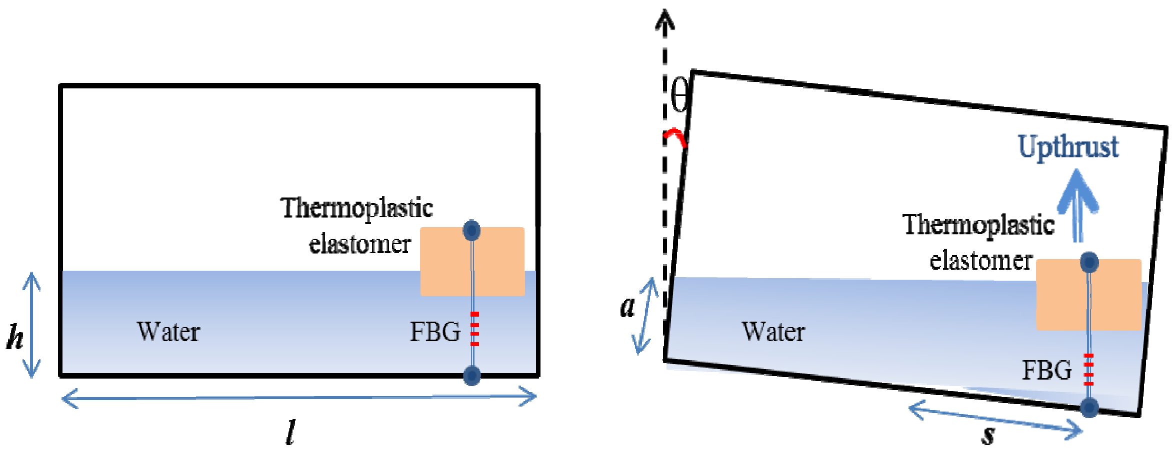


Figure 1. Schematic of FBG sensor and its principle.

2.2 Tilt sensor design and its principle

The tilt sensor design proposed in this paper works on the principle of buoyancy of liquids. The schematic of experimental arrangement is shown in Fig. 2. A nonabsorbent pad of thermoplastic elastomer is floating in the liquid container. This floating pad is tied to the bottom of the container through an FBG sensor as shown in Fig. 2(a). When the liquid container tilts as shown in Fig. 2(b), the pad sinks more and it feels upthrust. The more the container tilts, the more is the upthrust.



(a) (b)

Figure 2. Schematic and principle of the proposed tilt sensor.

The initial (before tilting) water level in the container is 'h'. The height of the water level on the left side of the container keeps going down with increasing angle of inclination. At a particular angle of inclination (θ), the height of the water level on the left side of the container is given as

$$a = \frac{h(x.y+l.w) - l^2.w.tan(\theta)/2}{l.w+x.y.cos(\theta)} \tag{3}$$

Where x & y are the length and breadth of the floating pad, l & w are the length and breadth of the liquid container.

The change in the liquid level at the point of FBG = Water level after tilt – Water level before tilt

$$\Delta h = [(l/2+s).sin(\theta) + a.cos(\theta)] - h \tag{4}$$

Hence, the upthrust felt by FBG sensor is calculated by calculating the weight of the liquid displaced by the floating pad due to the change in liquid level given in equation (4) as

$$F = \rho.(x.y.\Delta h).g \tag{5}$$

Where ρ is the density of the liquid and g is the gravity. The strain induced in the FBG due the upthrust F is calculated as

$$\varepsilon = \frac{Normal\ strass\ on\ FBG}{Elasticity\ of\ the\ fiber} = \frac{F/_{\pi r^2}}{E} \tag{6}$$

Where r is the radius and E is the modulus of the elasticity of the fiber. The change in the Bragg wavelength ($\Delta\lambda_B$) of the FBG sensor due to the upthrust F can be calculated using equation (2) as

$$\Delta\lambda_B = \varepsilon \times \text{strain-optic coefficient of the FBG } (\alpha) \tag{7}$$

The values of strain-optic coefficient (α) of the FBG sensors in communication wavelength range (1500nm – 1600nm) and in far infrared wavelength range (800nm - 900nm) are 1.2pm/µm and 0.67pm/µm respectively.

3. EXPERIMENTS AND RESULTS

The size of the liquid container used in the experiment is 47x15x15cm^3 and the size of the thermoplastic elastomer pad is 19.7x9.7x2.5cm^3. The liquid used in the experiment is water. The experimental arrangement similar to Fig. 2 was setup. One edge of the water container is elevated/demoted step by step to give it a positive/negative inclination to the container and then the response of the FBG which is tied to the floating pad at the other end of the container is recorded. The change in the Bragg wavelength ($\Delta\lambda_B$) of the FBG with the change in angle of inclination (θ) is shown in the Fig. 3. The simulated values of change in Bragg wavelength ($\Delta\lambda_B$) for discrete values of θ are obtained using equations (5), (6) and (7). The simulated data points are also shown in Fig. 3. A very good match is found between the experimental and simulation results. The resolution of angle of inclination (θ) in this design depends on the size of the container (l & w), the size of floating pad (x & y), and the distance of FBG from the center of the container (s) as established in equations (3) and (4). The resolution of the tilt sensor presented here is 0.0028degree/pm, which is higher than that of any other tilt sensor design presented so far in the literature. The size of this tilt sensor might be too big to be implemented for many applications.

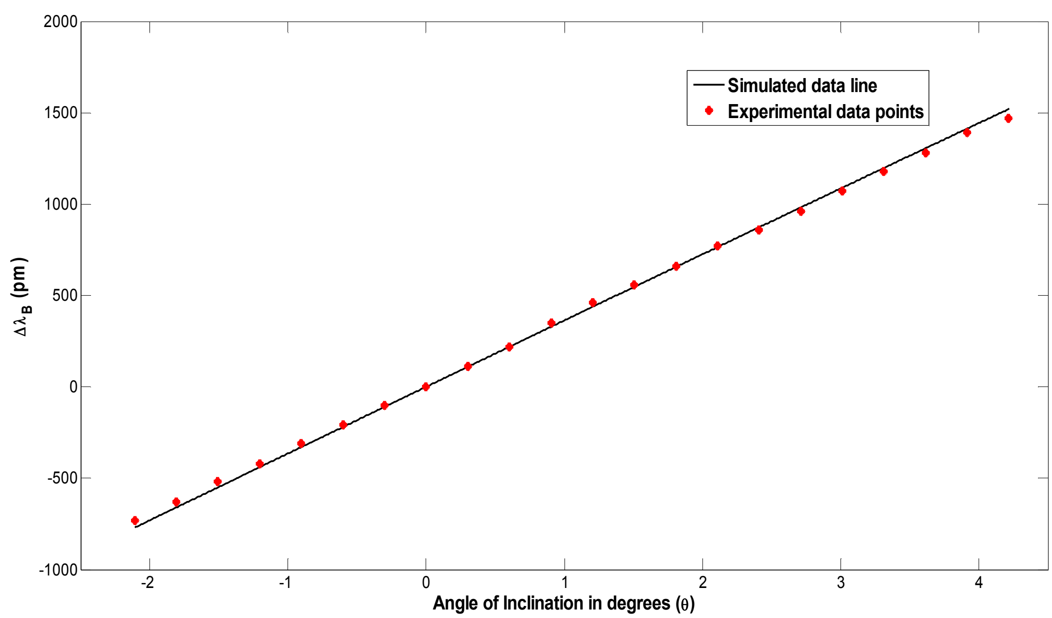


Figure 3. Response of FBG with change in angle of inclination.

Furthermore, an experiment was performed with a cylindrical liquid container with smaller dimensions. A circular pad of thermoplastic elastomer of diameter 9cm is used in this case. The schematic of the experimental setup is shown in the Fig. 4. Again, the container is tilted and the response of the FBG is recorded. The change in Bragg wavelength with the angle of inclination is shown in Fig. 5. Clearly, the resolution is lower because the size of the floating pad and the size of the liquid containers are lower in this case. Also 's', the distance of the FBG from the center of the container is zero in this case (refer to Fig. 2(b)). The resolution of the tilt sensor is 0.056degree/pm, which is in the same order as of any other tilt sensor presented in the literature. The biggest advantage of such cylindrical design is that it is symmetrical about its axis; therefore, its response remains the same even if it is rotated, unlike the case of other tilt sensor designs.

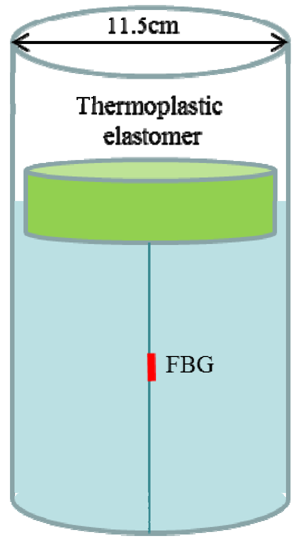


Figure 4. Schematic diagram of a cylindrical experimental setup.

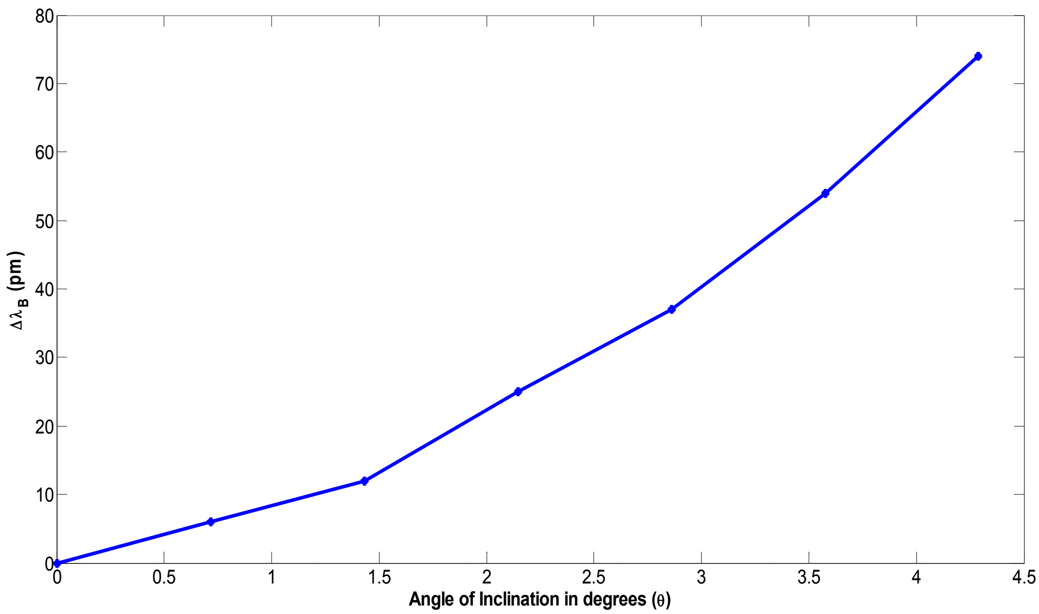


Figure 5. Response of FBG with angle of inclination for cylindrical setup.

4. CONCLUSIONS

The design of proposed FBG based tilt sensor is simple and does not involve any mechanical or optical complications. It is free from any mechanical bonding or mechanical joint and therefore, its performance is less likely to degrade for a long term monitoring application. It is highly sensitive and its resolution is also very high. However, the size of the tilt sensor dimensions might need be adjusted for some applications. When the dimensions are reduced to make it more practical, its resolution goes down. Still, in the most practical dimensions, its resolution is comparable (or in the same order) to that of other tilt sensor designs presented in the literature. Also, this buoyance-based FBG tilt sensor can be made in a symmetrical shape to avoid the effect of rotation. The sensor resolution can be further increased by using a liquid with a higher (than water) density.

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