A novel method to detect the liquid level based on the FBG sensor Part I: The structure design and performance analysis

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***Abstract*—This paper proposes a novel method to detect the liquid level. Specifically, a novel structure based on the diagram and the flexible hinge is presented, in which the Fiber Bragg Grating (FBG) is employed as the sensing element and temperature compensation is considered. The corresponding analytical model of the structure is developed, which shows that the strain of the FBG is a linear correlation with the liquid level. The presented sensor show superior range ($\pm 200mm$) and superior sensitivity ($23.80pm/mm$) when compared with some of the similar structures shown in the literature. To validate the analytical model, a Finite Element Model (FEM) is employed and the results showed that the analytical model is accurate. This paper aims to give the structure design and performance analysis for the sensor and the corresponding experiments will be given in our subsequent paper series Part II.**

Keywords-novel method; liquid level; FBG sensor; the measuring principle

I. INTRODUCTION

As one of the important means of industrial detection, liquid level detection plays an important role in the chemical industry, petroleum storage, and sewage treatment. Researchers have done a lot of work in liquid level detection, and different sensing techniques have been presented in the existed literature.

Jin et al presented a coaxial cylindrical capacitive sensor to detect Settlement of liquid level and analyzed the monitoring effect of the sensor [1]. Chetpattananondh et al presented a self-calibration method to measure the water level by utilizing an interdigital capacitive sensor[2]. Nevertheless, the electrical sensors are difficult to apply in the harsh environment, i.e. corrosive, flammable and explosive atmosphere. As a new measurement method, FBGs overcomes many problems existing in traditional measurement methods, such as being vulnerable to electromagnetic interference and chemical corrosion, as well as being difficult to realize multiplexing and so on. It has become an important research direction in liquid level measurement.

In the past few years, there are many kinds of structures based on FBG sensing technology have been presented. The sensors based on the surrounding medium refractive index of FBG, i.e. tilted, etched FBG or polymer FBG, need to be immersed directly in the liquid. Therefore, it limited the range of measurement due to the limitation of the physical length of the gratings [4-5]. To avoid this limitation, some researchers presented some novel structures. Guo et al presented a novel FBG liquid level monitoring sensor which is insensitive to temperature and based on the cantilever beam, however, the sensitivity of the sensor is not given in this paper [5]. Marques et al presented a liquid level monitoring system which is highly sensitive since the Fiber Bragg Grating is used, whose sensitivity is $10.21 \pm 0.09pm/cm$ [6]. Recently, Diaz proposed a liquid level measurement method based on FBG embedded in metal diaphragm, which has a temperature compensation function with a sensitivity of 2.8 pm/mm.[7]. To achieve the goal of detecting liquid level accurately, the highly sensitive liquid level sensor is urgently needed. In this work, we present a novel structure based on the diagram and the flexible hinge in which the Fiber Bragg Grating is employed as the sensing element and temperature compensation is considered. The presented sensor shows a

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superior range (±200mm) and superior sensitivity (23.80pm/mm) when compared with some of the similar structures shown in the literature. The analytical model of the sensor is developed to analyze the property of the sensor and further validated by the FEM.

Compared with the liquid level sensor mentioned in the literature mentioned above, our proposed liquid level sensor innovatively uses the diaphragm and flexible hinge structure. Because the diaphragm is very sensitive to the change of pressure and the flexible hinge can achieve precise magnification of small displacement, the sensitivity and liquid level detection range for the proposed sensor are enhanced greatly. At the same time, by optimizing the size of the sensor, the performance of the sensor can be further improved flexibly according to the needs of detection.

The remainder of the paper is constructed as follows: The operating principle and the structure design of the sensor are given in Sec. II; Sec. III gives analysis and verification of the developed sensor model using the Finite Element Method, and the conclusion is given in Sec. IV.

II. OPERATING PRINCIPLE AND STRUCTURE DESIGN OF THE SENSOR

A. The sensing principle of the FBG

As shown in Figure 1, when broadband light satisfying Bragg conditions enters into the optical fiber, it will be reflected as narrowband light. And the Bragg condition is expressed as follows [8]:

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

in the formula, λ_B is the central reflection wavelength of FBG, n_{eff} is the effective coefficient of refractive index of fiber core, and Λ is the inherent period of grating.

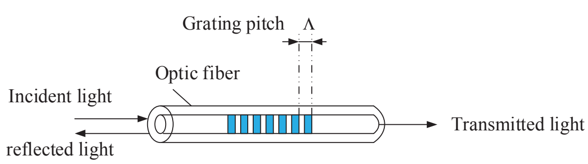

Figure. 1 The sensing principle of the FBG

The variation of the central wavelength of FBG is affected by both temperature and strain. When the strain and temperature of FBG change, the shift of wavelength can be expressed as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e) \cdot \Delta\varepsilon + (\alpha_n + \alpha_A) \cdot \Delta\text{T} \tag{2}$$

where $\Delta\lambda_B$ is the change of the central wavelength of the FBG, $\Delta\varepsilon$ is the change of the strain of the FBG, and ΔT is the change of the temperature near the FBG. p_e、 α_n and α_A represent the strain optical coefficient, the thermal expansion coefficient and the thermo-optical coefficient of light respectively.

B. The operating principle and the structure design of the presented liquid level sensor.

The liquid level monitoring scheme proposed in this paper is mainly based on the principle of the connector. The schematic diagram of the monitoring system is shown in Figure 2. The designed liquid level sensor is connected with the liquid tank with a drainage hose. In this system, the FBG interrogator and the computer are used to obtain the FBG data.

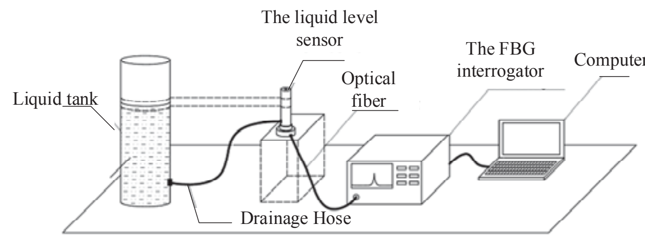

Figure. 2 The monitoring system of the liquid level.

As shown in Fig. 3, the liquid level sensor consists of five parts. When the liquid level of the measured tank changes, the liquid level inside the sensor will also change, and the metal diaphragms will deform accordingly. And then the deflection at the position of FBG 1 and FBG 2 will be amplified by the flexible hinge. In the following, we will develop the analytical relationship between the FBG's strain and the liquid level.

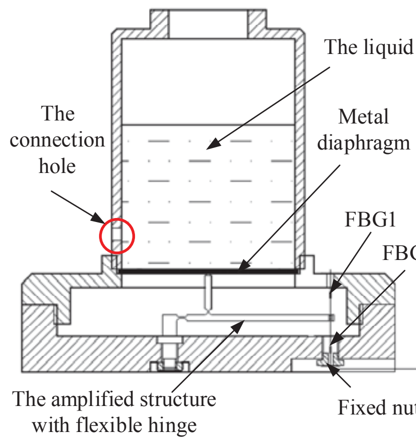

Figure.3 Schematic diagram of liquid level sensor.

When the variation of the liquid level is ΔH, the variation of the pressure at the position of the diaphragm can be obtained as follows:

$$\Delta P = \rho \cdot g \cdot \Delta H \tag{3}$$

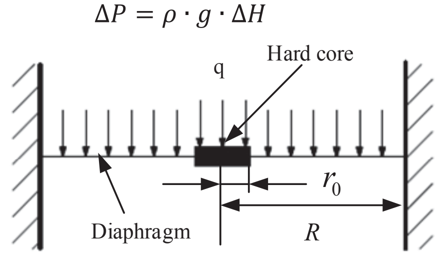

Figure. 4 The force model of the diaphragm with a hardcore

The force model of the diaphragm with hardcore is shown in Fig.4. The hardcore is induced by the connection of the amplified mechanism to the diaphragm. In the figure, q is the uniform load acting on the surface of the metal diaphragm, r is the radius of the metal diaphragm, and D is the computational stiffness of the metal diaphragm.α is the diaphragm's effective radius and r_0 is the hardcore's radius. And the deflection of the center on the diaphragm can be expressed as follows:

$$\omega = \frac{q}{64D}\left[R^4 - {r_0}^4 + 4R^2{r_0}^2 ln\frac{r_0}{R}\right] = \frac{3(1-\mu^2)qR^4}{16Eh^3}[1-\left(\frac{r_0}{R}\right)^4 + 4\left(\frac{r_0}{R}\right)^2 ln\frac{r_0}{R}] \quad (4)$$

In Formula 4，D represents the stiffness of the plate，and it can be expressed as follows:

$$D = \frac{E_m h^3}{12(1-\mu^2)} \quad (5)$$

Where E_m ,h, and μ denote the elastic modulus of the diaphragm, the thickness of the diaphragm and the Poisson's ratio of the diaphragm respectively. The variation of the deflection at the diaphragm's center can be expressed as follows:

$$\Delta\omega \approx \frac{3\rho g\Delta H(1-\mu^2)a^4}{16Eh^3} \quad (6)$$

To increasing the sensitivity of the presented model, the deflection of the diaphragm will be amplified by a mechanism shown in Fig. 5. Based on the principle of the lever, when the center of the diaphragm is displaced downward, the deformation of the magnifying mechanism except for the other parts of the flexible hinge portion is negligible, and the angle of rotation is also very small. Therefore, we can believe that the ΔABC and the ΔADE in the simplified figure are similar triangles. The deflection of the position used to connect the FBG will be enlarged as follows:

$$\Delta L = \frac{L_1 + L_2}{L_1}\Delta\omega \quad (7)$$

However, the ΔL and the Δω will affect each other for the three aspects: (1) The axial stiffness of the optical fiber;(2) the rotation stiffness of the flexible hinge. In what follows, the effects of the two aspects of the performance of the sensor will be explored in detail.

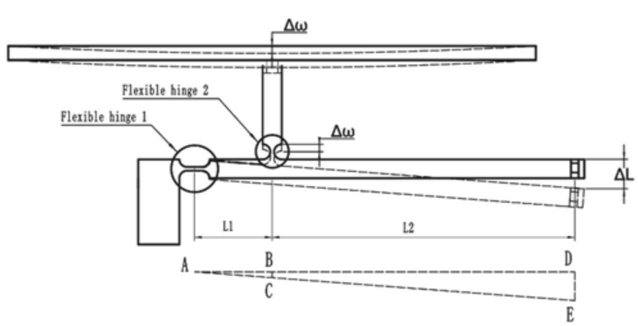

Figure.5 The designed structure of the amplified mechanism

(1) The effect of the axial stiffness of the FBG on the performance of the sensor.

Firstly, we assume an equivalent concentrated force F for the surface force induced by the liquid is employed. Based on the equilibrium conditions, the force F can be obtained as follows:

$$F = \pi \cdot R^2 \cdot q/4 \quad (8)$$

And now we assume that the force generated by the axial stiffness of the optical fiber is F_1, and then the F_1 can be expressed as follows:

$$F_1 = E_g A\varepsilon_F = E_g A\frac{\Delta L}{L} \quad (9)$$

where E_g is the optical fiber's Young's elastic modulus, A is the optical fiber's cross-sectional area and L is the optical fiber's initial length. Based on the equilibrium conditions, the force F_2 applied to the center of the diaphragm by the amplified mechanism can be obtained as follows:

$$F_2 = k_1 \cdot F_1 \quad (10)$$

where $k_1 = \frac{L_1+L_2}{L_1}$. And then the comprehensive force applied on the center of the diaphragm and be obtained as follows:

$$F_0 = F - F_2 = F - k_1 \cdot F_1 \quad (11)$$

And then the modified deflection of the center of the hardcore can be obtained as follows:

$$\omega = \frac{3R^2(1-\mu^2)F_0}{4E\pi h^3} \quad (12)$$

Based on (12), (11), (10), (9), (8) and (7), the following formula can be obtained as follows:

$$\Delta L = \frac{3\pi qLk_1R^4(1-\mu^2)}{16E\pi h^3 L + 12k_1R^2(1-\mu)E_g A_0} \quad (13)$$

in our case, the $12k_1R^2(1-\mu)E_gA_0 \ll 16E\pi h^3L$, and then the (11) can be further expressed as follows:

$$\Delta L \approx \frac{3\pi \cdot R^4 \cdot q \cdot k_1 \cdot (1-\mu^2)}{16E\pi h^3} \quad (14)$$

From (12), it can be seen that the effect of the reaction Force of Fiber Bragg Grating due to Axial Deformation can be ignored.

(2) The effect of the rotational stiffness of the flexible hinge on the performance of the sensor.

The flexible hinge used in the liquid level sensor belongs to fillet straight beam flexible hinge. Figure 6 shows the structure of the flexure hinge. We define that b is the flexible hinge's width, h is the flexible hinge's height, t is the thickness of the straight beam part in the middle of the flexible hinge, l is the straight beam's length and R_F is the radius of the bow. Based on the work of the Zuo et al [9], the rotational stiffness of the flexible hinge used in our study can be obtained as follows:

$$k_R = \frac{E_F bt^3}{12l} + \frac{E_F bR_F^2}{12f} \quad (14)$$

where E_F is the Young's modulus of the flexible hinge, and f is expressed as follows:

$$f = \int_{-\pi/2}^{\pi/2} \frac{\cos\theta}{\left(\frac{t}{R} + 2 - 2\cos\theta\right)^3} d\theta = \frac{12\beta^4(2\beta+1)}{(4\beta+1)^{5/2}} arctan\sqrt{4\beta+1} + \frac{2\beta^3(6\beta^2+4\beta+1)}{(4\beta+1)^2(2\beta+1)} \quad (15)$$

where $\beta = \frac{R}{t}$

Based on the equilibrium conditions of the flexible hinge 1, the force F_2 can be obtained as follows:

$$F_2 = \frac{\Delta\omega \cdot k_1}{l_1^2} \tag{16}$$

And then the comprehensive force applied to the center of the diaphragm can be obtained as follows:

$$F_0 = F - F_2 = F - \frac{\Delta\omega \cdot k_1}{l_1^2} \tag{17}$$

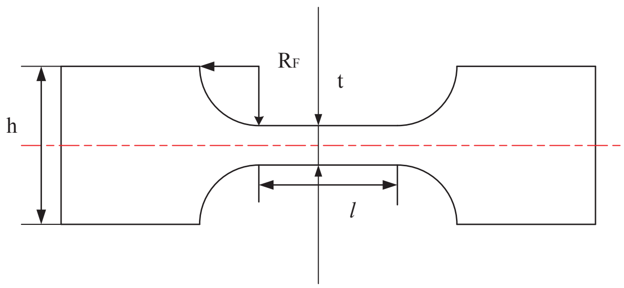

Figure.6 The structure of the flexible hinge.

Based on (17), (12) the variation of the deflection on the center of the diaphragm can be obtained as follows:

$$\Delta\omega = \frac{3\pi R^4(1-\mu^2)\Delta q {l_1}^2}{16E\pi h^3 {l_1}^2 + 12R^2(1-\mu^2)k_R} \tag{18}$$

Based on the principle of the lever, the ΔL can be obtained as follows:

$$\Delta L = k_1\Delta\omega = \frac{k_1 \cdot 3\pi R^4(1-\mu^2)\Delta q {l_1}^2}{16E\pi h^3 {l_1}^2 + 12R^2(1-\mu^2)k_R} \tag{19}$$

Based on the (19), the effects of the k_R on the ΔL can be obtained. And the strain of the FBG ε_F can be obtained as follows:

$$\varepsilon_F = \frac{\Delta L}{L} = \frac{k_1\Delta\omega}{L} = \frac{k_1 \cdot 3\pi R^4(1-\mu^2)\Delta q {l_1}^2}{16E\pi h^3 {l_1}^2 + 12R^2(1-\mu^2)k_R} \cdot \frac{1}{L} \tag{19}$$

For the FBG of the 1500 bands, the central wavelength drift of the FBG due to the strain can be expressed as follows:

$$\Delta\lambda_B = 1.2 \times 10^6 \cdot \varepsilon_F \tag{20}$$

And then the presented liquid level sensor's sensitivity can be obtained as follows:

$$\frac{\Delta\lambda}{\Delta H} = \frac{k_1 \cdot 3.6 \cdot 10^3 \cdot \pi R^4(1-\mu^2)\Delta q {l_1}^2}{16E\pi h^3 {l_1}^2 + 12R^2(1-\mu^2)k_R} \cdot \frac{1}{L}(pm/mm) \tag{21}$$

If the structural and material parameters of the structure are determined, the sensitivity of the sensor will be obtained analytically.

The flexible hinge 2 in the amplification mechanism is a bow flexible hinge. Because the Young's modulus of the flexure hinge 2 is large in the vertical direction, the deformation of the whole amplification mechanism will not be affected by the deformation of the flexure hinge 2.

In the process of detecting the change of system liquid level, the wavelength of FBG will be affected by the liquid level and the temperature of the monitoring system at the same time. Therefore, if we want to detect the liquid level accurately, we must eliminate the effect of temperature on the measurement results.

To eliminate the influence of temperature and compensate for the temperature of the sensor, two FBGs are used as shown in Fig. 7. Specifically, the FBG1 and FBG2 are respectively located on the upper and lower sides of the end of the hinge amplifying mechanism, the change of the liquid level will have the opposite effect on the center wavelength of FBG1 and FBG2. Meanwhile, the FBG1 and FBG2 are in the same environmental temperature, which will have the same effect on the center wavelengths of FBG1 and FBG2. The strains of FBG1 and FBG2 can be expressed as：

$$\begin{aligned} \varepsilon_A &= \varepsilon_F + \varepsilon_T \\ \varepsilon_B &= -\varepsilon_F + \varepsilon_T \end{aligned} \tag{22}$$

Making a difference in the wavelength variation of FBG1 and FBG2, and then averaging the difference, we can eliminate the influence of temperature on the measurement result and obtain more accurate liquid level information. Based on the principle of the difference, the following formula can be obtained.

$$\varepsilon_F = \frac{\varepsilon_A - \varepsilon_B}{2} \tag{23}$$

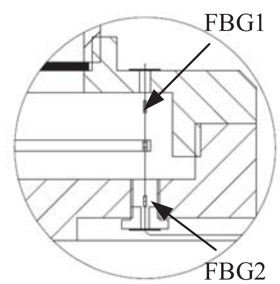

Figure. 7 The configuration of the FBGs for temperature compensation.

III. VALIDATION OF THE DEVELOPED ANALYTICAL MODEL USING THE FEM

The software ANSYS WORKBENCH is used to generate the Finite element simulation（FEM）of the structure as shown in Fig. 8. To obtain the sensitivity of the sensor, the different values of surface pressure, i.e. Finite element analysis of sensor model is carried out every 10 Pa from 0 Pa to 100 Pa. And the deformations of the position to connect the FBG under the tested scenarios are further shown in Fig.9. Note that the pressure is used to simulate the pressure of the liquid.

Other parameters in FEM simulation include Young's modulus of flexible hinge $E_F = 2 \times 10^9 Pa$, Young's modulus of metal diaphragm $E_F = 1.98 \times 10^9 Pa$, thickness of diaphragm $h = 0.5mm$, radius of diaphragm $R = 50mm$ and parameters of flexible hinge.

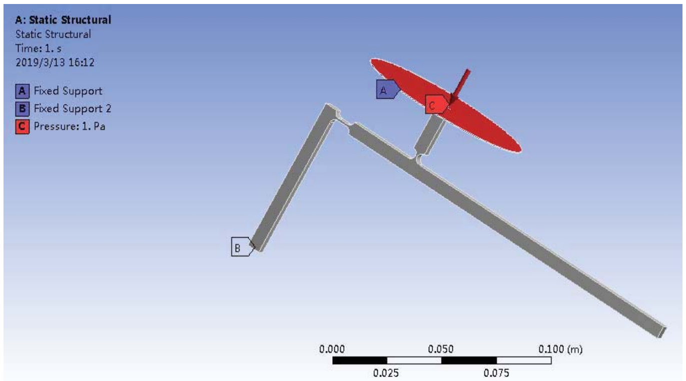

Figure. 8 The FEM generated by ANSYS WORKBENCH.

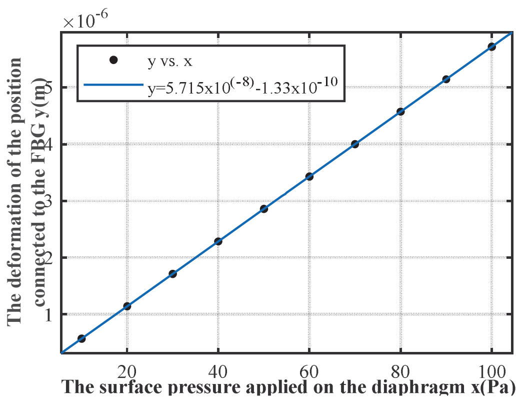

Figure. 9 The deformation of the position connected to the FBG.

Assuming that the liquid in the sensor is water, the height of the liquid level is increased continuously in the unit of 1mm. Fig. 10 shows the theoretical and simulated values of the central wavelength shift of FBG varying with the liquid level from 1 mm to 10 mm.

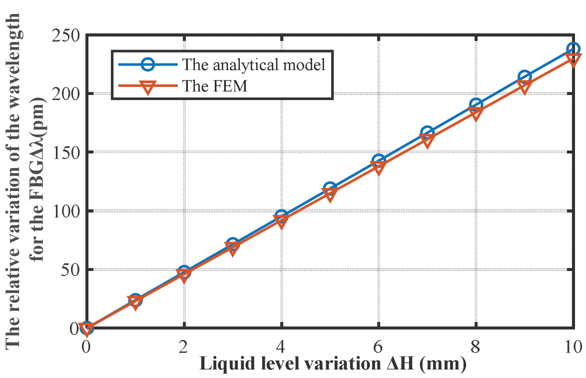

Figure. 10 The variation of the wavelength of the FBG under the different variations of the liquid level.

From Fig. 10, it is so clear that the analytical results are accurate with the results from FEM. Based on the developed analytical model, the sensitivity of the sensor is obtained as 23.80pm/mm.

Compared with the liquid level sensor proposed by M. Consales et al, the sensitivity of the liquid level sensor designed in this paper is ten times higher in the same measuring range, and the measuring range of the sensor can be further improved by optimizing the parameters. [10].

IV. CONCLUSIONNME

This paper presented a novel method to detect the liquid level. Specifically, a novel structure based on the diagram and the flexible hinge is presented, Fiber Bragg Grating (FBG) is the sensing element of the structure and temperature compensation is considered. The corresponding analytical model of the structure is developed, which shows that there is a linear relationship between the strain of the FBG and the liquid level. The presented sensor shows a superior range (±200mm) and superior sensitivity (23.80pm/mm) when compared with some of the similar structures in the literature. To validate the analytical model, a Finite Element Model (FEM) is employed and the results showed that the analytical model is accurate. This paper aims to give the structure design and performance analysis for the sensor and the corresponding experiments will be given in our future work.

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