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Research on a novel variable-area optical fiber gas flow sensor

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ABSTRACT

Based on the structure of the traditional variable area flow meter and the principle of the optical fiber measurement, this article designed a new type of fiber Bragg grating (FBG) gas flow sensor. The tapered tube of the sensor is mounted vertically, and the float inside the tube moves up and down under the effect of the airflow. The longitudinal displacement of the float is converted to the deflection of the cantilever which bonded FBG under the action of magnetic force. Thus the flow variation could be transformed into the deflection of the cantilever, resulting in the change of FBG wavelength and phase. By detecting the change of the optical signal, the gas flow can be derived. The experimental results show that the sensor has the characteristics of good linearity and fast response time. The proposed sensor can determine the flow of air within 1–6.5 m^3/h and the sensitivity of the sensor approximately reaches 0.22 $nm/(m^3/h)$. By optimizing the parameters of the sensor, the sensitivity and the accuracy can be improved accordingly.

1. Introduction

Flow value is an important parameter in industrial control and production. In the field of flow measurement, the mechanical rotor sensor [1] has been widely applied, its measurement principle is simple, the technology is relatively mature, but the measurement error is large and the accuracy is relatively low. The vortex flow sensor [2,3], the turbine flow sensor, electromagnetic flow sensor, volumetric flow sensor and acoustic Doppler flow sensor [4–6] have developed subsequently, their accuracy are relatively high. But the cost of the sensors are expensive, their applications are limited and the results of the detection usually affected easily by the outer electromagnetic field. Therefore, researchers continue to explore new methods of measurement and develop novel flow sensors.

Optical fiber is a new kind of optical passive component and develops quickly in the last decades, it is widely used in many fields [7,8], such as industrial production, medical treatment, manned spacecraft project, military application and scientific research. Many scholars applied optical fiber in the field of flow measurement, and developed new types of optical fiber flow sensor. Optical fiber flow sensors have many advantages [9] over traditional sensors, such as wide application extent, high precision, small volume, insensitivity to influence of electromagnetic field, intrinsically safe, etc. The optical sensor can measure the multi-parameters and work under severe environment [10].

Based on the study of different flowmeter measurement principles and the principle of optical fiber sensing [11–13], this paper proposes a novel optical fiber gas flow sensor. The sensor uses FBG as basic sensing element based on cantilever and variable area measurement structure (which also known as rotameter). The method provides a higher accuracy in measurement and it is suitable for the transmission of remote signal. It is conductive to realize remote control and build sensor networks.

2. Sensor structure and principle

The schematic diagram of the proposed optical fiber gas flow sensor is shown in Fig. 1. A float is placed inside a tapered tube which installed vertically, it moves up and down freely with the airflow, and the height of the float has a direct correspondence with pipe flow. The float is produced by the magnetic material and couples the magnets outside the pipe via magnetic field, the magnetic steel is connected with the cantilever beam which pasted with FBG, thus the displacement of the float is converted into the axis strain of the fiber Bragg grating and the gas flow can be gotten by measuring the center reflecting wavelength shift of the FBG.

According to the hydrodynamics, the gravity optical of the float is F_1, the fluid's buoyant force to float is F_2, the sum of differential

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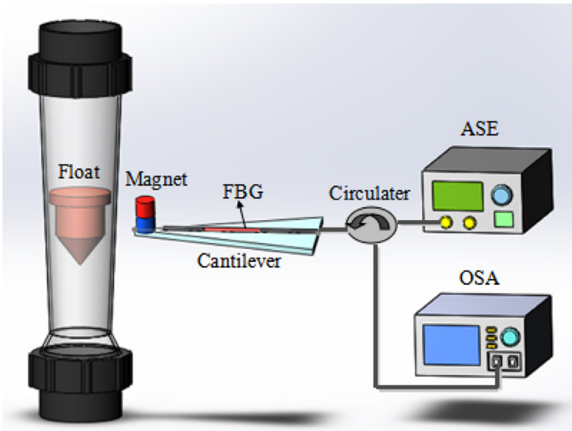

Fig. 1. Structure of the optical fiber flow sensor.

pressure force and the friction float received is F_3 and they can be expressed respectively as follow:

$$F_1 = V_f \rho_f g$$
$$F_2 = V_f \rho g \quad (1)$$
$$F_3 = \xi \frac{\rho v^2}{2} A_f$$

where V_f is the volume of the float, ρ_f is the density of the float, ρ is the density of the fluid, ξ is the drag coefficient, when the float is in equilibrium position:

$$F_1 - F_2 - F_3 = 0 \quad (2)$$

The velocity of flow through annular region v can be represented as:

$$v = \sqrt{\frac{2V_f g(\rho_f - \rho)}{\xi \rho A_f}} \quad (3)$$

A_0 is the area of annual region, and the flow can be achieved:

$$q_v = A_0 v = \partial A_0 \sqrt{\frac{2V_f g(\rho_f - \rho)}{\rho A_f}} \quad (4)$$

The volume flux of the flow is q_v, the flow coefficient is ∂, $\partial = \sqrt{1/\xi}$, A_0 varies with the changes of flow and the relationship between circulation area, A_0 and the height of the float h can be expressed:

$$A_0 = \rho\pi(R^2 - r_f^2) = \pi(2hr \tan\varphi + h^2 \tan^2\varphi) \quad (5)$$

The cone angle of the tapered tube φ is small, so its square can be ignored. The gas flow is simplified as the linear function of the height of float:

$$q_v = \partial\pi dh \tan\varphi \sqrt{\frac{2V_f g(\rho_f - \rho)}{\rho A_f}} \quad (6)$$

where d is the maximum diameter of the float.

The cantilever beam which pasted with FBG is the sensing unit [14] of the sensor, its structure is shown in Fig. 2. When measured pressure F forces on the free end of the cantilever, the strain of one point on beam can be expressed as:

$$\varepsilon_x = \frac{6(l - x)}{EAd} F \quad (7)$$

l is the length of cantilever, x is the distance from the select point to the fixed end, E is the elasticity modulus of the beam, d and A are the thickness and the cross-sectional area of the beam respectively.

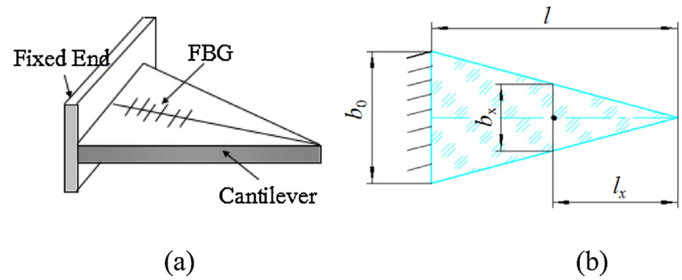

Fig. 2. (a) Cantilever pasted with FBG. (b) The structure of the cantilever beam.

The formula of the cantilever cross-section is:

$$A_x = db_x = db_0 \frac{l_x}{l} = db_0 \frac{l - x}{l} \quad (8)$$

The theory formula [15] of the resilient cantilever beam is given as

$$\varepsilon = \frac{6l}{Eb_0 d^2} F \quad (9)$$

It has been proved that the strain remains unchanged in the center axis of the cantilever, avoiding the requirement for the position where the sensing unit is pasted. The deflection at the free end of the beam is:

$$y = \frac{6l^3}{Eb_0 d^3} F \quad (10)$$

The Bragg equation and the peak shift expression [16] of the fiber Bragg grating which is pasted in the center axis of the beam is derived as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon \quad (11)$$

P_e is the elastic-optic coefficient. According to the formula above, the relation between the center wavelength offset of the FBG and the gas flow is

$$\Delta\lambda_B = q_v \frac{d\lambda_{B0}(1 - P_e)}{\partial l^2 \pi D \tan\varphi} \sqrt{\frac{\rho A_f}{2V_f(\rho_f - \rho)}} \quad (12)$$

Thus the gas flow can be calculated by detecting the shift of the Bragg center wavelength.

3. Experimental results and discussions

The diameter of the pipe is 15 mm which is equal to the maximum diameter of the tapered tube, and the cone angle of the tube is 1.15°, the weight of the float is 14 g which is calculated according to the fluid mechanics, the cantilever beam is made of organic glass with length l = 160 mm, width b_0 = 4 mm and thickness d = 1 mm. Experimental measurement system is shown in Fig. 3, air flow which generated by the pump is the experimental measuring object, the flow moves upward through standard flowmeter (thermal gas mass flowmeter which accuracy is ±1%) and the proposed optical fiber sensor in turn. Optical fiber sensor is calibrated and test by the standard flowmeter. In addition, the article designs a by-pass pipe which plays a protective and adjusting role in measurement.

The device was fixed on the experimental platform, and ensures the sensor was installed vertically. Spectrum was produced by the Amplified Spontaneous Emission (ASE), and the shift of Bragg reflecting wavelength was measured by the Optical Spectrum Analysis (OSA). Keep the environment temperature and the working pressure constant relatively, Fig. 3 shows the reflection spectra of the optical sensor under different air flow.