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An optical fiber sensor for simultaneous measurement of flow rate and temperature in the pipeline

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ABSTRACT

An optical fiber sensor was proposed and studied for the simultaneous measurement of flow rate and temperature. It includes a capillary steel tube, an adjustable target and two fiber Bragg gratings (FBGs). The two fiber Bragg gratings were fixed in the tube by glue, and they could be protected well. One end of the tube was assembled in the protective shell, the other end was connected to a target. Flow rate and temperature would both cause the wavelength shifts of FBGs. Without causing a large adjustment, the flow sensitivity of the proposed sensor could be adjusted by only assembling a properly designed target. On the basis of simulation, the proposed sensor was fabricated and realized the simultaneous measurement of flow rate and temperature, which was verified by experiments. Due to the limitation of experiment system, the flow rate accuracy was up to 2.27% in the range of 5–16 m^3/h, and the temperature accuracy was under ± 1 °C in the range of 23–83 °C. With advantages of compact size, high sensitivity, wide measurement range and small pressure loss, it has a great potential application in many areas.

1. Introduction

Flow rate and temperature are important parameters to pipeline transportation which can reflect the operation condition of the pipeline. The effective measurement of those parameters is significant in many industry areas, such as medical treatment, chemical engineering and so on [1–3]. Now many kinds of flowmeter sensors have been proposed and applied, such as electromagnetic flowmeter [4], differential pressure type flowmeter [5] and ultrasonic flowmeter [6], yet they are not good enough to meet the requirements in some special occasions. With some features of optical fiber technique, such as corrosion resistance, multiplex capability, electromagnetic immunity and compact size [7,8], optical fiber sensors are widely concerned as a promising technology, and then many different kinds of optical fiber flowmeters have been proposed, such as traditional vortex-based fiber flow sensor [9,10], target-type-based fiber flow sensor [11,12], optical fiber thermal gas flowmeter [13,14], optical turbine flowmeter [15,16].

FBG is widely applied in the optical fiber sensors because of its low fabrication cost, stable characteristic and multiplex capability [17]. Most of the optical fiber flow rate sensors were proposed based on the principle that FBG was sensitive to strain. However, its temperature-sensitive property, which would influence the measurement precision of strain or flow rate, should be also focused on. So temperature decoupling is significant to the sensor and it restricts the practical application of FBG sensors. In 2004, Shoichi Takashima et al. present a flow rate sensor on the basis of Karman vortex [18], two cantilevers are applied to measure the frequency of the vertex which can ignore the temperature effect. The sensor can achieve a liquid flow rate measurement between 0 and 1 m^3/h whose measurement range was limited in practical application. In 2010, Jia et al. proposed a target-type flow sensor for simultaneous measurement of flow-rate/temperature [12], and the sensor had a good performance. But its triangle cantilever caused a relatively large pressure loss, which restricted its measurement range, only from 1.44 to 7.92 m^3/h. Caldas et al. proposed a hot-wired flowmeter with a resolution of 0.08 m/s which fully utilize the FBG's temperature characteristic [19]. However, the sensor structure is too vulnerable to apply for the pipeline fluid measurement, and the liquid has relatively high thermal conduction which is not suitable for the application of hot-wired sensor.

To improve our last achievement [20], the capillary steel tube with the target was proposed to increase the sensitivity of flow rate to adapt to the application and achieve the temperature measurement at the same time. A pair of FBGs were fixed in the capillary steel tube which worked as a protector. By fixing a target on the free end of the capillary, the flow rate sensitivity of the sensor was improved apparently. By the way, the temperature could be obtained by the shift of central

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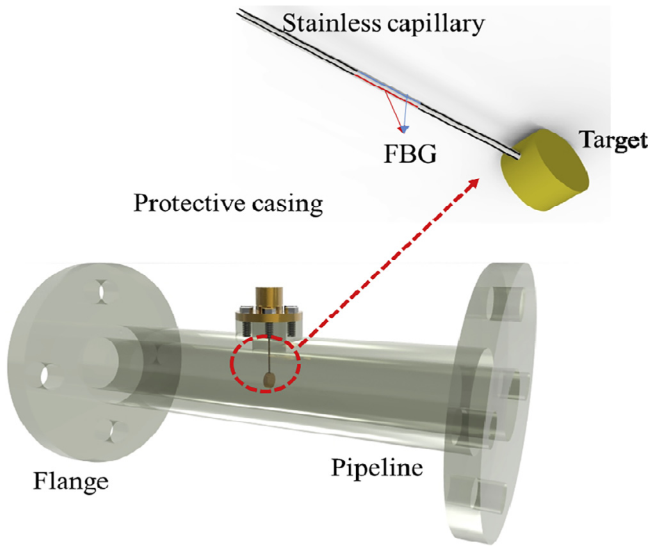

Fig. 1. The sensing structure of the proposed sensor.

wavelength between the resonance wavelengths of the two FBGs. Meanwhile, with the compact sensing probe, the proposed sensor would produce a low pressure-loss in actual measurement.

2. Sensor structure and measurement principle

The sensing structure is composed of a section of pipe with flanges, a target, a capillary steel tube, a pair of FBGs, and a protective casing, which is shown in Fig. 1. The pipe with flanges makes the installation of the sensor easier. The target is placed in the center of the pipeline, and the plane of the target is perpendicular to the flow direction. The free end of the capillary is inserted into the target, and the other end is fixed in the protective casing. The protect casing prevents the fluid from flowing out of the pipe and fixes the capillary steel tube. Besides, the two FBGs were put through the capillary steel cantilever and stuck symmetrically along its inner wall. Meanwhile, the plane of the two FBGs is parallel to the direction of the fluid. The capillary would be distorted by the impact force of the flow, while the strain is transferred to the two FBGs. Consequently, the resonance wavelengths of FBGs shift with the change of fluid. The FBG with longer resonance wavelength shift to the red side and the other FBG shift to the blue side.

The relations between the deformation and the flow rate are calculated by using the finite element analyze (FEA) method. Then the model of the sensor was established. And the relative parameters in the simulation were introduced as follows. Stainless steel was selected as the material of the capillary for its good mechanical characteristic. The target's diameter was set to 10 mm. The inner diameter and the outer diameter of capillary were 0.6 mm and 1 mm, respectively. The capillary's length was 40 mm, and 10 mm length of the capillary was inserted into the target to hold the target. Pure water was selected as the fluid. To reduce the calculation consumption and increase the computation efficiency, half of real part was adopted as the model. Fig. 2 showed the simulation result of the model.

Then, the boundary conditions were set according to the actual situation. One end of the capillary beam was fixed and the other end was free. The two FBGs stuck on the inner wall of the capillary steel tube, sense the positive and negative strain respectively. The strain on the lines of the inner wall along the assembled positions of two FBGs was calculated. The strain under different flow rates is shown in Fig. 3. The reason that the strain fluctuates up and down is because of the grid limitation, but it basically reflects the strain because it is consist with the coarser mesh. As the previous mentions, the plane formed by the two gratings is parallel to the flow direction. According to the knowledge of elastic mechanical, the two line sense the negative and positive strain separately, and the magnitude of the strain on the two FBGs was the same. The position of x = 35 mm around was chosen to place the FBGs. The reason why choose here is that the strain in there was relatively big, and the FBG has a little distance to the ending of the capillary which the FBG cannot be easily damaged.

The relationship between the strain and the flow rate at x = 35 mm was plot in Fig. 4. After comparing and consulting the relevant books of fluid mechanics, the relationship between the strain on the capillary and the flow was quadratic. According to the fiber grating strain measurement formula [20]:

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

where ε is the strain on the capillary, and P_e is the effective photo-elastic coefficient of fiber. The relation can be established between the flow rate and the wavelength shift (assuming that the resonance wavelength of the FBG is 1550 nm):

$$y = 0.0058x^2 + 0.0011x - 0.0004 \quad (2)$$

where x represents the flow rate in the pipeline, and y stands for the FBG wavelength drift at different flow rate.

The sensor can realize the simultaneous measurement of temperature and flow rate because the two FBGs are located in essentially the same temperature field. And the temperature sensitivity can be eliminated by multiplying a coefficient to one FBG. And that is equivalent to obtaining temperature and strain information by solving a binary equation system.

3. Experimental setup

The experiment system which could provide liquid at different flow rate and temperature was built. As shown in Fig. 5, it includes a pump, a standard magnetic flowmeter, a standard temperature sensor, a standard pressure sensor, a water tank, a heating rod, a control box and our proposed sensor. Water with different flow rate and temperature was provided by the pump and the heating rod, respectively. And the water tank has the function of heat preservation because of the double layer design with an insulation layer in the middle. The flow rate and water temperature were controlled by the control box. The standard magnetic flowmeter(a product of Bei Fei Automation Instrument with accuracy of 0.3% in the range of 2–20 m^3/h, and its operating temperature range is −20 °C to 60 °C) was applied as the calibrate instrumentation for the flow measurement of the proposed optical fiber sensor. The temperature sensor is applied to correct the temperature characteristic of the proposed sensor.

The sensor was fabricated according to the previous description. And the fixture of the FBGs is the focus of sensor production. Make sure that the two FBGs are not wrapped in the capillary tube. The central reflection wavelengths of the two FBGs were 1554.216 nm and 1558.110 nm respectively at room temperature, which is aimed to achieve the differential measurement. Their grating lengths were 5 mm.

4. Results and discussion

4.1. Temperature sensing property

Firstly, the sensor's temperature characteristic was analyzed by the experiment. The temperature calibration was carried in an insulation cup which has the merit of slow temperature change. TFX430 Precision Thermometer (Ebro) with the accuracy of ± 0.05 °C in the range of −100 °C to 500 °C was applied in the experiment. The temperature response curves of FBGs were shown in Fig. 6. The temperature sensitivities of FBG1 and FBG2 were 0.02742 nm/°C and 0.02602 nm/°C respectively, and their fitting degrees were more than 0.99935. The temperature sensitivity of the sensor is higher than that of the bare FBG