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Novel integrated optical fiber sensor for temperature, pressure and flow measurement☆

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ABSTRACT

A novel integrated optical fiber sensor was proposed for temperature, pressure and flow measurement. One fiber Bragg grating (FBG) was fixed in the target for temperature measurement. A couple of FBGs, which were stuck on the inner wall of a hollow cylindrical cantilever, were used to measure flow rate. Another couple of FBGs were fixed on the outer wall of a thin-walled cylinder to measure pressure. Theoretical relationships between the Bragg wavelengths of FBGs and temperature, pressure and flow rate, have been established by numerical analysis respectively. Meanwhile, experiments have been carried out to obtain the performance of the proposed integrated sensor. Experimental results showed that the resolutions of temperature, pressure and flow rate were 0.1 °C, 0.006 MPa, 0.17m^3/h and the measurement ranges were 10∼95 °C, 0∼10 MPa and 0∼18.5m^3/h, respectively. In addition, the precision of sensor in temperature, pressure and flow rate were 0.12%, 0.5%, 1.5%, respectively. As we know, the proposed flowmeter is more compact with good resolution, wide measurement range, high accuracy and easy fabrication.

1. Introduction

Pipeline plays an indispensable role in our daily life. Temperature, flow rate and pressure are the key parameters of pipeline. The precise measurement of these parameters is of great importance because they are closely related to the safety of operation and the economic efficiency of the pipeline system [1,2]. Various sensors have been developed for the monitor of pipeline. However, most of the typical sensors can only realize the measurement of one or two of the parameters, such as temperature, pressure and flow rate. And a few sensors can measure the three parameters simultaneously which are mainly traditional electric sensors. However, the traditional electric sensors may have some potential safety hazards which limit their applications in some situations with strong radiation or flammable and combustible materials. Optical fiber sensor is the kind of sensor which has the merits of intrinsic safety and anti-electromagnetic [3–7]. Due to their excellent sensing performances and physical characteristics, optical fiber sensors have become a hot research topic [8–10].

With the rapid development of optical fiber sensing technologies, many novel optical fiber sensors, for the measurement of temperature, pressure and flow rate, have been proposed, such as optical fiber Fabry-Perot (F-P) sensor, fiber Bragg grating (FBG) sensor, polarization-maintaining photonic crystal fiber (PM-PCF) sensor, Mach-Zehnder (M-Z) interferometer sensor and so on [11–15]. Optical fiber sensor is a promising choice for simultaneous measurement of temperature, pressure and flow rate. Besides, it can be cascaded and is more convenient to achieve distributed measurement and remote monitoring.

Since the mature processing technology and low fabrication cost, FBG has been widely applied in many areas [16,17]. Meanwhile, FBG which works as a narrow bandwidth reflector can be easily used in series, thus FBG is chosen to realize the integrated sensor for pipeline. Up to now, there are many pressure sensors based on FBG as shown in Table 1.

In the earlier time, a target-type flow rate sensor based on FBG had been proposed by us, which adopted an isosceles- triangle-

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Table 1
The general pressure sensors base on FBG.

Types	Sensitivity	Measurement range
Polymer [19]	1.71 nm/MPa	0MPa–0.1MPa
Double shell cylinder [20]	0.0937 nm/MPa	0MPa–4MPa
Diaphragm [21]	1.57 nm/MPa	0MPa–1MPa

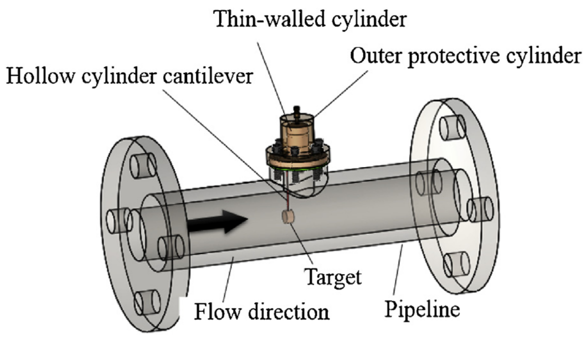

Fig. 1. Structure of the integrated optical fiber sensor for temperature, pressure and flow measurement.

shape cantilever as a strain transfer mechanism [18]. A couple of FBGs were stuck on the symmetry axis on the two parallel plane of the cantilever respectively. But the FBGs were easily broken by the flow impact. In this paper, instead of triangular cantilever, hollow cylinder cantilever, which the FBGs were stuck in, was proposed to work as the strain transfer mechanism. It could protect the sensing probe effectively.

In this paper, a novel integrated optical fiber sensor was proposed which combines several sensors and realizes the simultaneous measurement of the pressure, flow rate and temperature synchronously. Also, new target-typed sensing probe and thin-walled cylinder were applied for flow rate and pressure measurement respectively. And the measurement sensitivity of flow rate was improved compared with the probe-type sensor [22]. Theoretical relationships between the Bragg wavelengths of FBGs and temperature, pressure and flow rate have been established. The feasibility of the integrated sensor has been verified by finite element simulation. In addition, the sensor was fabricated and its characteristic was studied and verified by experiment. It is of small size, simple structure and wide measurement range.

2. Sensing structure and measurement principle

The schematic diagram of the proposed integrated optical fiber sensor is shown in Fig. 1. The integrated sensor consists of a target, a hollow cylindrical cantilever, a thin-walled cylinder, an outer protective cylinder and five fiber Bragg gratings (FBGs). The target is in the center of the pipeline. The target was fixed at the free end of the cantilever. The other end of the cantilever is fixed in the bottom of the thin-walled cylinder. Meanwhile, the cantilever is perpendicular to the axis of the pipeline. Specific information of the integrated sensor and measurement principle will be introduced as follows.

2.1. Temperature measurement principle

As shown in Fig. 2, FBG1 is fixed in the free end of hollow cylinder cantilever for temperature measurement. The free end of hollow cylinder cantilever is fixed in the target. The position of FBG1 can be protected from the impact of the fluid. As a result, FBG1 is only affected by the change of fluid temperature. The shift of FBG1's

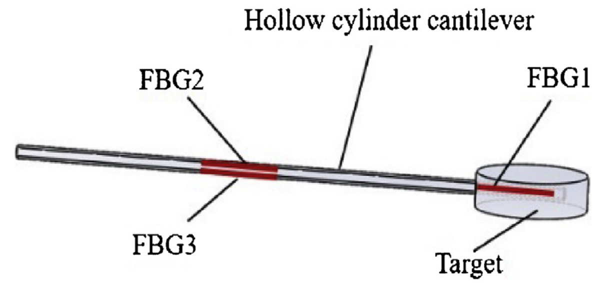

Fig. 2. Schematic diagram of the probe for temperature and flow measurement.

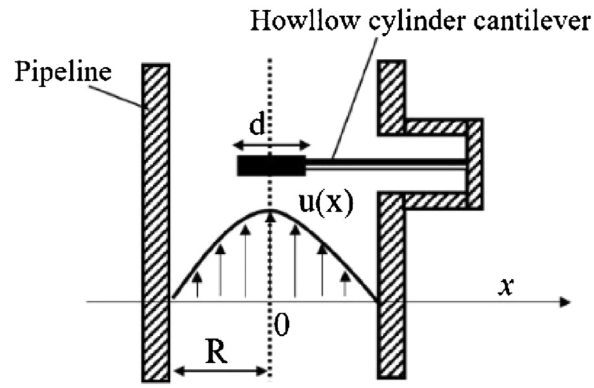

Fig. 3. Flow rate distribution of fully developed flow in pipeline.

Bragg wavelength, $\Delta\lambda_{B1}$, with temperature ΔT can be described as:

$$\frac{\Delta\lambda_{B1}}{\lambda_{B1}} = (a+\xi)\cdot \Delta T \tag{1}$$

where λ_{B1} is the Bragg wavelength of FBG1, a is the coefficient of thermal expansion of optical fiber, and ξ is the thermo-optic coefficient of the optical fiber.

2.2. Flow measurement principle

A couple of FBGs (FBG2 and FBG3) were fixed on the inner wall of hollow cylinder cantilever for flow measurement, as shown in Fig. 3. The two FBGs are stuck symmetrically along the inner wall of the hollow cylindrical cantilever. At the same time, the plane where the two FBGs were stuck on is perpendicular to the cross section of pipeline. The sensor was assembled in the vertical direction over the pipeline. In that situation, the fluid can be developed fully so that the flow rate can be measured even the fluid velocity is very low.

With the impact of fluid, the cantilever is distorted and the distortion is transferred to the two FBGs. As a result, Bragg wavelengths of the two FBGs shift oppositely. One FBG shows red shift with the stretching and the other shows blue shift with the squeezing.

When the fluid is fully developed, the flow rate at a random place within the pipeline can be described as [23]:

$$u(x) = 2\cdot V\cdot \left[1-\left(\frac{x}{R}\right)^2\right] \tag{2}$$

where x is the radial dimension from the center of the pipeline, V is the average flow rate, R is the radius of the pipeline as shown in Fig. 3.

With a part of fluid impact on the surface of hollow cylindrical cantilever, the kinetic energy of the fluid will be transformed into