Modeling and Simulation Research of the Self-gain Optical Fiber Differential Pressure Sensor Based on Damping Piston

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Abstract. This paper takes a modeling and simulation study on the self-gain optical fiber differential pressure sensor based on damping piston. Firstly, proposes the structure of mechanical packaging sensor probe based on the damping piston, and designs the sensor system; then, carries out the theoretical research on the sensor and builds the intensity modulation function and sensing model of the sensor. Simulation experiments based on the theoretical model are also conducted. The experimental results show that: changing the stiffness of the damping spring can change the detection range of the sensor. In certain stiffness of the damping spring, a sensor’s detected differential pressure $\Delta P$ is in good linearity with the sensor output value $H$, and the sensor has high sensitivity, whose output value can get self gain. The research shows that the optical fiber differential pressure sensor is of good detection performance and can meet the needs of different detection occasions.

Introduction

The differential pressure sensor is one applied to measure the fluid pressure differences in different positions, which is widely used in industrial production, testing, scientific experiments, safety monitoring and other fields, such as the seal leakage detection, detection of automobile tail pressure difference, monitoring the pressure drop at the front and rear of the engine compressor of an aircraft, mine ventilation real-time measurement, liquid level measurement, measurement of fluid flow, the micro positive pressure measurement on the constant temperature and humidity workshop and biological research space, micro leakage measurement of containers, medical devices blood flow measurement and so forth. Nowadays, there have been differential pressure sensors with different principles, such as resistive, capacitive and inductive, restrictor-type, magnetic fluid and MEMS and other sensors, among which the resistive and capacitive ones are common, while other types did not get the promotion due to poor practicability, limitations or being still in the concept stage. But the resistive and capacitive differential pressure sensors are also limited in many occasions. Because of this, many scholars are committed to the improvement of structures and performance of differential pressure sensors so that they can better serve fields of modern industrial testing [1-5].

Meanwhile, optical fiber sensor technology with its incomparable advantages over many traditional sensors has attracted more and more attention in modern sensor researches [6-9]. In recent years, there have been scholars committed to the study of optical fiber pressure sensor. Taiwan's Hao-Jan Sheng, et al, America Jose.L.A.V et al respectively put forward an optical fiber pressure sensor structure based on Bragg grating [10-11]; Japan Seiichiro Kinugasa proposed a reflective optical fiber pressure sensor [12]; Tong Chengguo et al designed a fiber differential pressure sensor based on the spring tube structure [13], but current researches haven’t conducted in-depth study on the realization of sensors, rationality of the probe structure and other key factors. In view of this, this paper proposes a self-gain optical fiber differential pressure sensor based on damping piston, and studies its structure and performance so as to further develop the research on the differential pressure sensor, pushing forward the design and promotion of the new differential pressure sensor.
Organization of the Text

Transducer Structure Design

Structure of the Sensor Probe

Figure 1. Probe structure.

As shown in Figure 1, the sensor probe is mainly composed of the end cover, cylinder, piston, spring, high transmission film, reflective film and other parts. The shape of the end cover is a cylinder, and the central axis is a thread hole and a high transmission sheet is installed at the end. The thread hole is matched with the external thread sleeve transmitting/receiving fiber bundles which are installed and fixed. An inner opening of the end cover is provided with a groove to position the spring. The inner side of the sensor is fixedly provided with a damping spring with the same structure and rigidity, and one end of the spring is fixed on the inner top of the end cover groove and the other side is fixed on the piston. The centers of the piston on two ends are installed with reflectors to reflect the incident light. Meanwhile, seal rings are mounted on appropriate positions of the end cover and the piston to prevent the infiltration of external fluid and surrounding fluids which may affect the measurement results.

The working principle of the sensor’s probe: when the fluid pressures are equal on both sides of the detection chambers, the piston does not have axial displacement, and the optical intensity signals on two sides of the probe receiving fiber output are equal; when there is pressure difference for the fluid on both sides of the detection chambers, the piston is out of balance and slides towards the side with lower pressure. It will compress the damping spring on the side and extends the damping spring on the other side. Meanwhile, the optical intensity signals on two sides of the probe receiving fiber output vary, which will achieve the gaining effect by enlarging the output value through the photoelectric conversion and signal processing.

Mathematical Model

In the reflective intensity modulated fiber optic sensor, the light emitted from the output optical fiber $TF$ is irradiated onto the reflector, and is coupled into the receiving optical fiber $RF$ with the reflection of the reflector. As is shown in Figure 2, there are usually 3 position relations between the reflective...
taper end face and the receiving optical fiber end face, but only when the two end faces intersect can the reflected light be received by the receiving optical fiber.

The analysis shows that the fiber intensity modulation function $M$ is mainly determined by the intersection area of the reflective taper end face and the receiving optical fiber end face. In order to simplify the model, it is not difficult to calculate the fiber intensity modulation function $M$ if the fiber exit light’s field intensity is in uniform distribution:

$$
M = \begin{cases} 
0 & x_1 \leq l - r \\
0.5 x_1^2 (\theta_1 - \sin \theta_1) + 0.5 r^2 (\theta_2 - \sin \theta_2) & l - r < x_1 < l + r \\
\frac{r^2}{x_1^2} & x_1 \geq l + r
\end{cases}
$$

In the formula: $l$ is the center distance for the transmitting fiber and receiving fiber; $r$ is the radius of the receiving fiber; $\theta_1$ and $\theta_2$ are the central angles of the intersected reflective taper end face and the receiving optical fiber end face; $x_i$ is the endface radius of the reflective taper.

And:

$$
\theta_1 = 2 \arccos \frac{x_1^2 + l^2 - r^2}{2 x_1 l}
$$

$$
\theta_2 = 2 \arccos \frac{-x_1^2 + l^2 + r^2}{2lr},
$$

$$
x_i = r_i + 2d \tan(\arcsin NA)
$$

In the formula: $r_i$ is the radius of the transmitting fiber; $NA$ is the numerical aperture of the optical fiber; $d$ is the initial distance between the receiving fiber end face and the reflector.

In the above formula, $M$ is the fiber intensifying modulation function whose function curve is divided into the front slope curve determined by formula (2) and the back slope curve determined by formula (3). In order to make the sensor designed in this paper good linearity and sensitivity, the initial state of the sensor is made to work near the middle of the above front slope curve in the fiber intensity modulation function $M$, then the unilateral intensity modulation model of the sensor in this paper is:

$$
M_1 = \frac{0.5 x_{11}^2 (\theta_{11} - \sin \theta_{11}) + 0.5 r^2 (\theta_{12} - \sin \theta_{12})}{\pi x_{11}^2} & l - r < x_{11} < l + r
$$

$$
M_2 = \frac{0.5 x_{12}^2 (\theta_{21} - \sin \theta_{21}) + 0.5 r^2 (\theta_{22} - \sin \theta_{22})}{\pi x_{12}^2} & l - r < x_{12} < l + r
$$

In the formula: $x_{11}$ and $x_{12}$ are respectively the endface radiuses of the two sides sensor work on both sides of the fiber bundle reflective tapers when the sensor works; $\theta_{11}, \theta_{12}, \theta_{21},$ and $\theta_{22}$ are the central angles of the intersected reflective taper end face and the receiving optical fiber end face of the fiber bundles on both sides when the sensor works. Therefore, the mathematical model of the sensor can be expressed as:

$$
H = \frac{x_{12}^2 (x_{11}^2 (\theta_{11} - \sin \theta_{11}) + r^2 (\theta_{12} - \sin \theta_{12}))}{x_{11}^2 (x_{12}^2 (\theta_{21} - \sin \theta_{21}) + r^2 (\theta_{22} - \sin \theta_{22}))} = f(\Delta P)
$$
The relationship between the pressure difference $\Delta P$ on both sides of the sensor and the size of the output light signal can be obtained with the above mathematical model.

**Experimental Results and Analysis**

According to the above mathematical model, select the initial value $r_1 = r_2 = 1\text{mm}$, $NA = 0.5$, $d_0 = 0.866\text{mm}$, $L = 2\text{mm}$, and the output of the sensor is obtained through the simulation experiment when $\Delta x$ varies from $0\text{mm}$ to $0.3\text{mm}$ ($d_1$ from $0.866\text{mm}$ to $1.166\text{mm}$, $d_2$ from $0.866\text{mm}$ to $0.566\text{mm}$).

The $M_1-d_1$ curve of the side with the corresponding displacement increased (high pressure side) and the $M_2-d_2$ curve with the corresponding displacement decreased (low pressure side) are as shown in Figure 4 and Figure 5 below:

![Figure 3. High pressure side $M_1-d_1$ curve.](image1)

![Figure 4. Low pressure side $M_2-d_2$ curve.](image2)

![Figure 5. $H-\Delta x$ curve.](image3)

It’s easy to know from Figure 3 that the luminous flux at the high pressure side increases as the piston moves away, and has good linearity. This is because the initial state of the sensor works near the middle position of the front slope curve in its intensify modulation function $M$, namely, the reflective taper end face intersects the receiving fiber end. At the moment, with the increase of the distance $d$, the light intensity coupled into the receiving fiber increases, so the high pressure side’s output value $M_1$ (nondimensional parameter) is on the increase, and maintains good linearity; it’s easy to know from Figure 4 that the output value $M_2$ (nondimensional parameter) at the low pressure side decreases as the piston moves away, which also has good linearity. Similar to the high pressure side, at this time, with the decrease of distance $d$, the optical intensity coupled into the receiving fiber decreases, so the low pressure side output shows a decreasing trend, and maintains a good linearity.

It is easy to judge from Figure 5 that the output in the form of ratio increases gradually from the constant value 1. When the output value $H$ (non dimensional parameter) is 1, namely, the sensor detects the fluid being no pressure difference, the piston is in the middle equilibrium position without sliding, and the two sides get equal output light intensity. When the sensor detects there is a pressure

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difference, the output light intensity of one side increases, while the other side reduces, and the output value \( H \) is rapidly increasing. Therefore, after the ratio processing, the output value \( H \) of the sensor has been greatly enlarged, which effectively improves the sensitivity of the sensor; Meanwhile, the output value of the sensor still maintains a good linearity.

**Conclusions**

This paper presents a new type of damping piston self-gain fiber differential pressure sensor. It first designs the differential pressure sensor’s probe and system, receiving the feasible structure of the fiber differential pressure sensor; then theoretical study of the sensor is carried out, contributing to the sensor’s intensity modulation model and sensor model, and simulation experiments on the basis of the theoretical model of it are implemented, analyzing the changing curve of the output luminous flux and the piston displacement, the curve of the flux ratio with displacement changes and the curve of the pressure difference \( \Delta P \) and flux ratio. Analyses show that the sensor has good linearity and sensitivity, and after the ratio processing, the output of the sensor is enlarged greatly, realizing the gain of output value.

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**References**


