Characteristics and Analysis of fiber Fabry-Perot Force Sensor

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Abstract. In this paper, a new optical fiber Fabry-Perot force sensor structure was designed based on the extrinsic optical fiber Fabry-Perot sensor. The sensor had the advantages of small size, high temperature and high pressure resistance, and had good resistance to strong electromagnetic interference. It can measure the friction force on the heat transfer pipe of steam generator in the harsh environment. The transmission characteristics of the sensor were analysed, and the performance of the sensor was simulated. Theoretically, the sensitivity of the sensor can reach 2.591 nm/N, and the minimum resolution can reach 11.309 N.

1. Introduction

As the hub of the primary circuit and secondary circuit system of the PWR(pressurized-water reactor) nuclear power plant, the steam generator plays a key role in the energy exchange between the primary circuit and the secondary circuit system. The heat transfer tube is an important part of the steam generator, and the damage of the heat transfer tube will cause serious safety and economic threats to nuclear power plants [1]. About 1/4 of the unplanned shutdowns of foreign PWR nuclear power plants are caused by the problem of the heat transfer tube of the steam generator, which has brought huge economic losses and nuclear safety issues [2]. Therefore, it is necessary to monitor the health of the heat transfer tube. The fretting damage caused by flow induced vibration is a major reason for the failure of the heat transfer tube, which mainly occurs between the heat transfer tube and the support plate and the vibration proof strip. The axial displacement and radial collision will occur between the heat transfer tube and the support plate and the vibration proof strip. Axial displacement will produce friction, and the measurement of friction can reflect the wear of heat transfer tube [3]. The environment of the heat transfer tube is very harsh, the temperature is as high as 350 ℃, the pressure is up to 15 MPa, and the distance between the heat transfer tube and the support plate and the vibration proof strip is very small. Therefore, in order to measure the wear between the heat transfer tube and the support plate and the vibration proof strip, a sensor with high temperature and high pressure resistance, waterproof and very small volume is needed.

At present, there are many kinds of force sensors, the common ones are piezoelectric sensor [4], current sensor [5], displacement sensor [6], piezoresistive sensor [7], light sensor [8] and so on. Traditional electrical and mechanical sensors are susceptible to electromagnetic interference, and cannot work normally in high-temperature water environments, and cannot be applied to complex working environments in steam generators. Fiber optic sensors have received extensive attention in nuclear
energy applications due to their high temperature and high pressure resistance and strong
electromagnetic interference resistance [9]. Optical fiber Fabry-Perot sensor has the advantages of small
volume, high sensitivity and simple modulation and demodulation principle, which is more suitable for
monitoring the stress of heat transfer tube in steam generator. Optical fiber Fabry-Perot sensors can be
divided into intrinsic and extrinsic types according to their structures [10]. In 1992, R.O. Claus, Murphy
et al. inserted two sections of optical fiber into a capillary glass tube, and glued the optical fiber and the
capillary glass tube together with epoxy resin, and successfully produced the first extrinsic optical fiber
Fabry-Perot sensor[11]. In 2012, W. H. Wang et al. studied a method to improve the pressure
measurement sensitivity of optical fiber Fabry-Perot sensors by leaving a vent between the capillary
glass tube and the optical fiber, so that the interference of temperature to pressure can be reduced during
the fabrication of the extrinsic optical fiber Fabry-Perot fiber cavity. The temperature measurement
sensitivity of this sensor is about 0.011 nm/℃, the pressure measurement sensitivity is about 5.18
nm/kPa, and the pressure measurement resolution is 38 Pa [12].

In the aspect of monitoring the wear of heat transfer tubes, there are few applications of optical fiber
Fabry-Perot force sensor. In this paper, an optical fiber Fabry-Perot force sensor was designed, which
can be used to detect the friction of heat transfer tubes, and then analyze the wear of heat transfer tubes.

2. Materials and Methods

2.1. Measuring principle
The core structure of the fiber Fabry-Perot sensor is the Fabry-Perot cavity, as shown in Figure 1. It is
mainly composed of two optical fibers with opposite end faces and a capillary glass tube wrapped around
them. The distance between the parallel end faces of the two optical fibers is the length of the cavity.

![Fig. 1 Fabry-Perot cavity](image)

The theoretical model of the light signal reflected from the Fabry-Perot Fabry cavity is based on the
principle of multi beam interference of parallel plates [13], as shown in Figure 2.

![Fig. 2 Principle of Fabry-Perot cavity interference](image)

Where \( \phi \) is the phase difference between any two adjacent beams. In the ideal case, the light source
is incident vertically into the Fabry-Perot cavity, and if half-wave loss is not considered, then the phase
difference \( \phi \) produced by a monochromatic light of wavelength \( \lambda \) going back and forth in the Fabry-
Perot cavity with the medium of air is:
\[ \phi = \frac{4\pi n L}{\lambda} = \frac{4\pi L}{\lambda} \]  

By integral summation of all wavelengths on the spectrum of broadband light source, the light intensity formula of reflected light is obtained as follows:

\[ I_R(\lambda) = \int_{\lambda_{min}}^{\lambda_{max}} \frac{R_1 + R_2 + 2\sqrt{R_1 R_2} \cos\left(\frac{4\pi L}{\lambda}\right)}{1 + R_1 R_2 + 2\sqrt{R_1 R_2} \cos\left(\frac{4\pi L}{\lambda}\right)} I_0(\lambda) d\lambda \]  

The light intensity distribution \( I_T(\lambda) \) of the transmitted light is:

\[ I_T(\lambda) = \int_{\lambda_{min}}^{\lambda_{max}} \frac{(1 - \sqrt{R_1 R_2})^2}{1 + R_1 R_2 + 2\sqrt{R_1 R_2} \cos\left(\frac{4\pi L}{\lambda}\right)} I_0(\lambda) d\lambda \]  

It can be seen from formulas (1) and (4) that the demodulation optical signal is related to the cavity length \( L \). The external pressure \( F \) applied on the sensor will change the cavity length of the Fabry-Perot cavity. The cavity length \( L \) is demodulated from the optical signal, and then the external force \( F \) can be obtained through the relationship between the cavity length \( L \) and \( F \), and then the external pressure change can be obtained.

The optical fiber Fabry-Perot force sensor designed in this paper measured the strain generated by the external force acting on the sensor. The strain will change the cavity length of the Fabry-Perot cavity of the sensor. Demodulating the change of the cavity length, and combined the relationship between the cavity length and strain, strain and external force, and then the external force can be measured.

2.2. Structural design

The sensor designed in this paper must first meet the working environment conditions in the nuclear power plant. The temperature of the primary circuit of the steam generator in the station is 350 °C, and the pressure is 15 MPa. The position of the heat transfer tube is high temperature and high pressure water environment, so the substrate material of the sensor needs to be able to withstand the high temperature of 350 °C and have higher hardness. After comprehensive consideration, 304 stainless steel material was selected as the substrate of the fiber Fabry-Perot sensor. The substrate structure is shown in Figure 3, the size is \( 9 \times 5 \times 0.8 \) mm (length × width × height), and the volume is very small, which can meet the requirements of measurement environment space for sensor volume.

![Substrate structure](image-url)
The substrate was composed of three platforms and two spring coils. The platforms at both ends were used to fix the sensor and ensure the parallelism of the optical structure of the whole sensor. The groove structure of the middle platform is the position of the Fabry-Perot cavity. The width between the two spring coils was the sensitive length of the sensor. The structure of the spring coils was more conducive to transfer the strain from the substrate to the Fabry-Perot cavity. Four small tables were designed around the substrate, which were used as welding positions when welding with other structures. A capillary glass tube with an inner diameter of 138 μm was placed in the groove structure in the middle of the substrate. The common single-mode or multi-mode fibers with the coating removed were inserted into both ends of the capillary. The end faces of the two fibers were strictly parallel aligned. The air cavity between the end faces of the two fibers was the Fabry-Perot cavity structure. The size of the groove structure of the substrate was strictly calculated to ensure that the capillary glass tube and the optical fiber structure were basically tangent to the substrate. The optical fiber was initially fixed on the substrate by coating UV glue on the curing points 1 and 2. Then the stainless steel cover plates of corresponding sizes were covered on the platforms at both ends to protect the optical fiber. The stainless steel cover plates were bonded with the substrate by epoxy resin glue. After the epoxy resin glue was completely cured for 24 hours, the optical fiber Fabry-Perot sensor was completed.

In order to measure the friction force of the heat transfer tube, the substrate of the optical fiber Fabry-Perot sensor needed to be welded into a structure, as shown in Figure 4.

Fig. 4 Welding the substrate on the beam of the structure: (a) schematic diagram and (b) physical picture

The two ends of the structure were fixed between the heat transfer tube and the fastener to bear the friction between them. There was a cross beam in the structure. The size of the cross beam was 15 × 5 × 6 mm (length × width × height). The sensor substrate was welded on the cross beam to improve the sensitivity of the sensor in measuring the friction. When the friction between the heat transfer tube and the fastener occurs, a force will be applied at one end of the structure. When the friction was applied at one end of the structure, strain will be produced on the substrate, and the Fabry Perot cavity will change accordingly. The friction can be measured by calibrating the relationship between the friction and the Fabry Perot cavity length. The actual structure of the sensor is shown in Figure 4 (b).

2.3. Transmission characteristics analysis
The two ends of the sensor designed in this paper are the platform, and the middle is the sensitive part. When measuring, the two ends are welded and fixed, and the sensitive length of the sensitive part in the middle is suspended. Therefore, the equivalent strain transfer model of the sensor structure can be assumed as the whole clamping transfer model, and the transfer model is shown in Figure 5.
In the figure, it is assumed that the length of axial deformation between the clamping points is $\Delta L$, and the deformation of platform and sensitive part is $\Delta L_s$ and $\Delta L_m$ respectively. Since 304 stainless steel is used for integrated cutting of metal substrate, the formula of material mechanics can be used to obtain the following results:

$$\Delta L_s = \frac{P L_m}{E_s A_s}, \quad \Delta L_m = \frac{P L_m}{E_m A_m}$$  \hspace{1cm} (5)

Among them, $E_s$ and $E_m$ are the elastic modulus of the clamping part and the sensitive part of the stainless steel substrate respectively. Because the materials are the same, their values are the same. $A_s$ and $A_m$ are the cross-sectional areas of the clamping part and the sensitive body respectively, and $P$ is the axial force between the fixed points of the clamping part at both ends of the substrate. It can be considered that the axial force between the fixed points of the clamping part in the model is the same, then:

$$\frac{\Delta L_s}{\Delta L_m} = \frac{E_s A_m}{E_m A_s} \frac{\varepsilon_m - A_m}{\varepsilon_s - A_s} = \frac{d_m h_m}{d_s h_s}$$  \hspace{1cm} (6)

Among them, $d_m$ and $d_s$ are the width of the cross section of the sensitive part and the clamping part respectively, $h_m$ and $h_s$ are the height of the cross section of the sensitive part and the clamping part respectively, and $\varepsilon_s$ and $\varepsilon_m$ are the strain of the clamping part and the sensitive part respectively. Because the cross-sectional area between the sensitive parts is a variable quantity, after the cross-sectional area of the sensitive part is modeled and calculated in MATLAB, they are replaced in formula (7). The relationship between the axial deformation $\Delta L$ of the whole substrate material and the deformation $\Delta L_s$ and $\Delta L_m$ of the clamping part and the sensitive part is as follows:

$$\Delta L = P \left( \frac{L_m}{E_s A_s} + \frac{L_s}{E_m A_m} \right) = P \left( \frac{L_s}{d_s h_s} + \frac{L_m}{d_m h_m} \right)$$

$$\Rightarrow \varepsilon = \frac{L_s}{L_c} + \frac{d_s h_s}{\sum \frac{d_s}{A_s}} \times \varepsilon_m$$

$$\Rightarrow \sum \varepsilon_m = \frac{L_s}{d_s h_s} \times \varepsilon,$$  \hspace{1cm} (7)

Where, $\varepsilon$ is the strain between the two clamping points of the substrate, and $\varepsilon_m$ is the strain of the sensitive part.

3. Results & Discussion
The force on the beam in the sensor structure can be simplified as the axial force $F$ on one end of the cantilever beam. Let the length of the beam be $l$, the width be $b$, and the height be $h$, as shown in Figure 6.

![Fig. 6 Stress model of beam](image)

The beam was compressed under force, ignoring the transverse deformation of the cross-sectional size, and the change in the length of the beam in the elastic range is:

$$\Delta l = \frac{Fl}{EA}$$  \hspace{1cm} (8)

The above formula is Hooke’s law, where $E$ is the modulus of elasticity and $A$ is the cross-sectional area. The deformation of the sensor’s Fabry-Perot cavity can be approximated as the change in the length of the beam, so the sensitivity of the sensor is:
For the sensor system, the number of CCD pixels and the thickness of optical wedge determined the theoretical resolution of the system, as shown in the following formula:

\[ \Delta l_{\text{min}} = \frac{H_{\text{max}}}{n_{\text{CCD}}} \]  

The number of CCD pixels \( n_{\text{CCD}} \) used by the hardware demodulation system is 2048. If the maximum and minimum thickness difference \( H_{\text{max}} \) of the optical wedge is 60 \( \mu \text{m} \), the corresponding thickness \( \Delta l_{\text{min}} \) of each pixel is 0.0292968 \( \mu \text{m} \), so 29 nm is the minimum shape variable of the Fabry Perot cavity. This resolvable minimum shape variable \( \Delta l_{\text{min}} \) determines the minimum resolution \( \Delta F_{\text{min}} \) of the sensing system:

\[ \Delta F_{\text{min}} = \frac{\Delta l_{\text{min}} E A}{l} \]  

Assuming that the elastic modulus \( E \) of 304 stainless steel is 193 GPa, that is, 193000 N/mm\(^2\), the dimensions of sensor beam are \( l = 15 \text{ mm}, b = 5 \text{ mm}, h = 6 \text{ mm} \). Then the sensitivity \( S \) and resolution \( \Delta F_{\text{min}} \) of the sensor are as follows:

\[ S = \frac{l}{E A} = 2.591 \text{ nm/N} \]  

\[ \Delta F_{\text{min}} = \frac{\Delta l_{\text{min}} E A}{l} = 11.309 \text{ N} \]  

In this paper, the displacement, strain and stress of the whole structure of the sensor were simulated and analyzed in SolidWorks. These three aspects are commonly used in the finite element static analysis. The displacement represents the offset of each calculation node relative to the original position under the external load, the strain represents the offset of each calculation node relative to the adjacent node under the external load, and the stress represents the internal force of each calculation node under the external load. The material used in the simulation was 304 stainless steel, its elastic modulus was 193 GPa, that was, 193000 N/mm\(^2\), and poisson's ratio was 0.29. The simulation temperature was set at 350 °C, one end of the sensor was fixed, and a force of 1000 N was applied on the other end to simulate the force transmitted to the sensor by the structure under test. The simulation analysis results are shown in Figure 7.
It can be seen from the figure that there was a certain degree of deformation in the position of the Fabry-Perot cavity. Combined with the hardware demodulation system, the cavity length change of the Fabry-Perot cavity can be demodulated, and then the external force can be measured. Both ends of the structure bore a large part of the force, which played the role of protecting the internal sensitive part.

4. Conclusions
The fiber Fabry-Perot force sensor based on the extrinsic fiber Fabry-Perot sensor was designed in this paper. It was resistant to high temperature and high pressure, and its volume was small. It can work normally in the high temperature and high pressure water environment of narrow space such as heat transfer tube, meeting the requirements of measuring the friction between heat transfer tube and fastener. The sensor had high sensitivity and resolution, the sensitivity can reach 2.591 nm/N, and the minimum resolution can reach 11.309 N. It had a good application prospect in nuclear power plant, deep-sea
exploration, aerospace and other harsh environments with strong electromagnetic interference, high temperature and high pressure.

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