2-D Fiber-optic Sensing Probe*

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Abstract A novel two-dimensional (2-D) intensity modulated optical fiber reflective sensing probe is presented. Theoretically, the 2-D modulating function of the sensing probe is deduced. The theoretical characteristic curves are given. Experimentally, a five fiber optic sensing probe has been designed and demonstrated. The experimental results are obtained. It is good agreement with the theoretical prediction.
Keywords Optical fiber; Response characteristic function, 2-D fiber optic sensor; Compensation technique
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0 Introduction

With the advantages of simplicity and low cost, many intensity type fiber-optic sensors are used for measurement and control in industry. But these sensors also have one main drawback: their accuracy can be greatly affected by the fluctuations of light source, the losses in the fiber system and the variations of the reflectivity of the reflecting devices. For this reason, to obtain good accuracy and stability, some convenient intensity compensation methods are needed. Hull-Allen proposed a compensation modulating method, which can overcome the variations of the reflectivity of a reflecting target[1], Yuan Libo suggested another reflective compensation modulating method[2]. The twin receiving technique for automatic compensation is used in both methods. According to the results of experiments, It can compensate the variations of light source intensity, the variations of the reflectivity of reflecting surface and the losses in fiber system[2,3] for both methods. These are the examples of one-dimensional (1-D) fiber optic sensors. In this paper, a fiber optic 2-D sensing probe is proposed. Its detailed theoretical analysis of the compensation mechanism and the characteristic function of the intensity optical fiber reflective sensor are given. Furthermore, the bundle cases are also discussed.

1 2-D fiber optic sensing probe structure

In general, optical fiber reflective sensor consists of a fiber as light source and another fiber as light receiver[4]. The light source fiber illuminates the reflecting surface, the receiving fiber receives the reflected light. By measuring the light intensity of the output of the receiving fiber, one can determine the 1-D displacement between the fiber and the reflecting target.

For this type sensor, the variations of light source intensity may directly lead to the unstable of the output of the sensor. To sensing two-dimensional (2-D) changing of the reflective target, a fiber optic sensing probe has been designed and demonstrated. The structure of the cross-section is shown in Fig. 1.

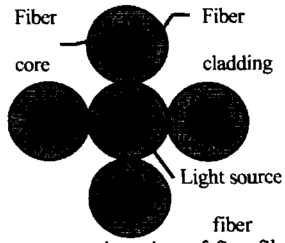

Fig. 1 The cross-section view of five-fiber-optic 2-D sensing probe

The sensing probe is not only able to sensing 2-D variation of the reflecting target, but can overcome the disadvantages such as the output signal unstable caused by the fluctuation of the light source and the reflectivity changing of target surface and the intensity losses in the fiber lines. In the sensing probe shown in Fig. 1, five fibers have been used as light source and receivers of reflecting light. The light is brought to the reflecting surface by the center fiber (see Fig. 1) such that the light impinges upon the reflecting surface. The light reflected from the reflecting surface is received by the four fibers arranged around of the illumination fiber. In Fig. 1, four receiving fibers have the same separate distance between the source fiber and the neighboring fibers. The working principle of the sensing probe shown in Fig. 2, it can measure the 2-D rotation angle on X and Y axis, respectively. The rotation angles θ_x and θ_y can be determined by the ratio of the outputs of

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the twin receiving fibers. For example, θ_x is determined by the output of the ratio I_2/I_4. This ratio is independent of the light source intensity and the reflectivity of the reflecting surface. Thus, the sensors are automatically compensated for variations in light source intensity and for variations in the reflectivity of the reflecting surface.

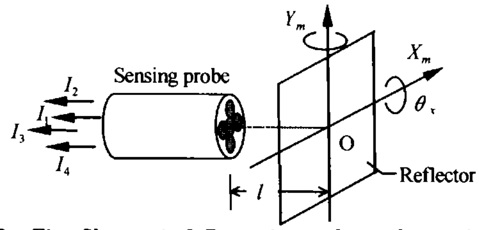


Fig. 2 Five-fiber-optic 2-D sensing probe working principle

2 Sensing response characteristics functions

The equivalent coordination aid analysis system is shown in Fig. 3. Using equation given by reference[5]

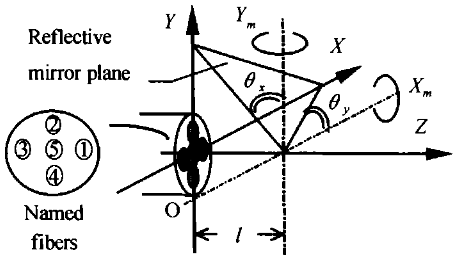


Fig. 3 Aid analysis coordination system for freedom 2D—two-dimensional variation (θ_x, θ_y)

$$I(x,y,z)=\frac{SRKK_0I_0}{\pi\omega^2(z)}\exp\left(-\sum_i\eta_ir_i\right)\exp\left\{-\frac{x^2+y^2}{\omega^2(z)}\right\}\quad(1)$$

Where, I_0 is the intensity of the light source coupled in the illumination fiber, $I(x,y,z)$ represents the light intensity at the point (x,y,z), S is the receiving area of the fiber end, i. e. the fiber core area, R is the reflectivity of reflective target, K_0 represents the losses in the input fiber, K represents the losses in the receiving fiber, $\exp\left(-\sum_i\eta_ir_i\right)$ represents the additional losses parameters in the receiving fiber caused by bends[2] and $\omega(z)$ is defined by

$$\omega(z)=a_0[1+\xi(z/a_0)^{3/2}\tan\theta_c]\quad(2)$$

Where a_0 is the radius of the fiber core, ξ is a coefficient parameter dependent on the type of light source and the coupling condition, θ_c is the maximum incident angle for the fiber.

Then one can analyze the optical fiber sensor's sensing properties and can also derive their response characteristic functions.

According to Fig. 4, assuming the reflective mirror rotated a small angle θ_x around axis X_m and then rotated an angle θ_y around axis Y_m. Thus, the mirror plane equation can be described as

$$x\tan\theta_y+y\tan\theta_x+z-l=0\quad(3)$$

Then the imaginary point $P(x,y,z)$ of the objective point $P_0(x_0,y_0,z_0)$ about the mirror plane can be calculated as

$$\begin{cases}x=x_0+2\tan\theta_y[x_0\tan\theta_y+y_0\tan\theta_x+z_0-l]M\\y=y_0+2\tan\theta_x[x_0\tan\theta_y+y_0\tan\theta_x+z_0-l]M\\z=z_0+2[x_0\tan\theta_y+y_0\tan\theta_x+z_0-l]M\end{cases}\quad(4)$$

where

$$M=(1+\tan^2\theta_x+\tan^2\theta_y)^{-1}\quad(5)$$

The central points of the real end position of the fiber 1, 2, 3 and 4 in the coordination system shown in Fig. 3 are

$$\begin{cases}F_1(d,0,0)\\F_2(0,d,0)\\F_3(-d,0,0)\\F_4(0,-d,0)\end{cases}\quad(6)$$

and the source fiber position is $F_5(0,0,0)$. Putting each fiber optic ends coordination position point into the formula (4), the imaginary coordination positions of the receiving fiber ends can be calculated as

$$F_1:\begin{cases}x_1=d+2\tan\theta_y(d\tan\theta_y-l)M\\y_1=2\theta_x(d\tan\theta_y-l)M\\z_1=2(d\tan\theta_y-l)M\end{cases}\quad(7)$$

$$F_2:\begin{cases}x_2=2\tan\theta_y(d\tan\theta_x-l)M\\y_2=d+2\tan\theta_x(d\tan\theta_x-l)M\\z_2=2(d\tan\theta_x-l)M\end{cases}\quad(8)$$

$$F_3:\begin{cases}x_3=-d-2\tan\theta_y(d\tan\theta_y+l)M\\y_3=-2\tan\theta_x(d\tan\theta_y+l)M\\z_3=-2(d\tan\theta_y+l)M\end{cases}\quad(9)$$

$$F_4:\begin{cases}x_4=-2\tan\theta_y(d\tan\theta_x+l)M\\y_4=-d-2\theta_x(d\tan\theta_x+l)M\\z_4=-2(d\tan\theta_x+l)M\end{cases}\quad(10)$$

Putting these coordinates into equation (1), for fiber j we have

$$I_j=\frac{S_j\cos\theta_x\cos\theta_yK_jK_0I_0}{\pi\omega_j^2(z_j)}\exp_j\left(-\sum_i\eta_ir_i\right)\cdot\exp\left\{-\frac{x_j^2+y_j^2}{\omega_j^2(z_j)}\right\}\quad(11)$$

here, $j=1,2,3,4$. And the output of the ratio expressed as

$$\frac{I_1}{I_3}=\frac{S_1K_1\omega_3^2(z_3)}{S_3K_3\omega_1^2(z_1)}\frac{\exp_1\left(-\sum_i\eta_ir_i\right)}{\exp_3\left(-\sum_i\eta_ir_i\right)}\cdot\exp\left\{-\frac{x_1^2+y_1^2}{\omega_1^2(z_1)}+\frac{x_3^2+y_3^2}{\omega_3^2(z_3)}\right\}\quad(12)$$

$$\frac{I_2}{I_4}=\frac{S_2K_2\omega_4^2(z_4)}{S_4K_4\omega_2^2(z_2)}\frac{\exp_2\left(-\sum_i\eta_ir_i\right)}{\exp_4\left(-\sum_i\eta_ir_i\right)}\cdot\exp\left\{-\frac{x_2^2+y_2^2}{\omega_2^2(z_2)}+\frac{x_4^2+y_4^2}{\omega_2^2(z_4)}\right\}\quad(13)$$

If the three fibers are of the same kind fiber and come from the same optical fiber cable, their losses and bends can be considered to be identical, then we have[5]

$$\begin{cases} S_1 = S_2 = S_3 = S_4 \\ K_1 = K_1 = K_3 = K_4 \\ \exp_1(-\sum_i \eta_i r_i) = \exp_2(-\sum_i \eta_i r_i) = \\ \quad \exp_3(-\sum_i \eta_i r_i) = \exp_4(-\sum_i \eta_i r_i) \end{cases} \tag{14}$$

thus the ratio output becomes

$$\frac{I_1}{I_3} = \frac{\omega_3^2(z_3)}{\omega_1^2(z_1)} \exp\left\{\frac{x_3^2 + y_3^2}{\omega_3^2(z_3)} - \frac{x_1^2 + y_1^2}{\omega_1^2(z_1)}\right\} \tag{15}$$

$$\frac{I_2}{I_4} = \frac{\omega_4^2(z_4)}{\omega_2^2(z_2)} \exp\left\{\frac{x_4^2 + y_4^2}{\omega_4^2(z_4)} - \frac{x_2^2 + y_2^2}{\omega_2^2(z_2)}\right\} \tag{16}$$

To simplify the output of the response characteristic functions (15) and (16), considering the sensing angle θ_x and θ_y are very small, therefore, approximately we have

$$\omega_1^2(z_1) \approx \omega_2^2(z_2) \approx \omega_3^2(z_3) \approx \omega_4^2(z_4) \approx \omega_0^2 = \text{Constant} \tag{17}$$

Thus, Eq. (15) and (16) become

$$\ln\left(\frac{I_1}{I_3}\right) = \frac{8ld}{\omega_0^2} \frac{1 + 3\tan^2\theta_x + 3\tan^2\theta_y}{(1 + \tan^2\theta_x + \tan^2\theta_y)^2} \tan\theta_y \tag{18}$$

$$\ln\left(\frac{I_2}{I_4}\right) = \frac{8ld}{\omega_0^2} \frac{1 + 3\tan^2\theta_x + 3\tan^2\theta_y}{(1 + \tan^2\theta_x + \tan^2\theta_y)^2} \tan\theta_x \tag{19}$$

This shows that the ratio of I_1/I_3 and I_2/I_4 is a function only of θ_x and θ_y, the rotation angle of the mirror around axis X_m and Y_m. Therefore, the ratio output is independent of the intensity of light source, reflectivity of the reflecting target and the fiber losses.

The 2-D fiber optic sensor' s response characteristic function can be expressed as a complex function

$$f(\theta_x, \theta_y) = \ln\left(\frac{I_1}{I_3}\right) + i\ln\left(\frac{I_2}{I_4}\right) = \rho(\theta_x, \theta_y) e^{i\varphi} \tag{20}$$

where, $\rho(\theta_x, \theta_y) = \sqrt{\{[ln\ (I_1/I_3)]^2 + [\ln\ (I_2/I_4)]^2\}}$ and $\varphi = \arg f(\theta_x, \theta_y) = \tan^{-1}[\ln\ (I_2/I_4)/ln\ (I_1/I_3)]$ represent the sensor' s output amplitude value and amplitude angle, respectively.

3 Discussions for 7 and 9 fibers bundles

Though more then 5 fibers bundle can be used to improve the detecting ratio of signal to noise. But the cost of the system will be increased. The number of fibers and the fiber relative distribution for 7 and 9 fiber bundles are discussed in this section. The cross-section of fibers from 7 fibers bundle is shown in Fig. 4, where the light source fiber is in the middle and it has six neighbors reflective receiving fibers. The six receiving fibers consist of a 60° triangle coordinate system. The two-dimensional detecting response functions can be deduced using the similar analysis method mentioned above. But the expression of the functions is more complicated then the five-fiber bundles. For the case of 9 fibers bundle, it has two cross-section structures as shown in Fig. 5.

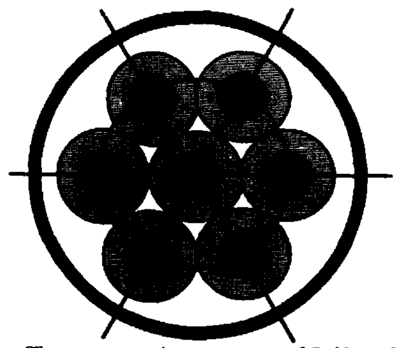
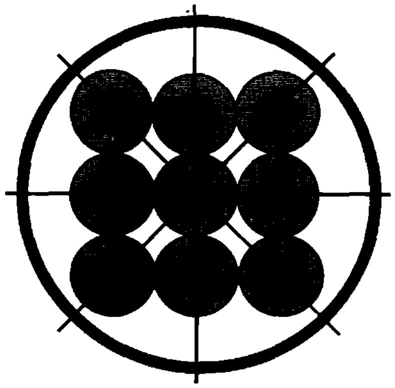
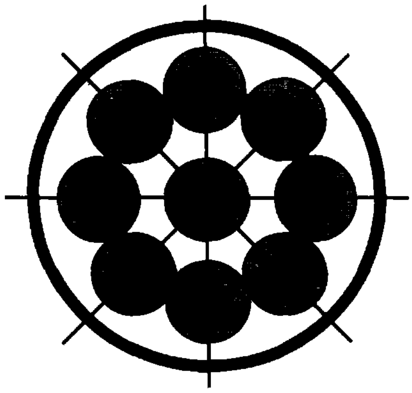


Fig. 4 The cross-section structure of 7 fibers bundle



(a)9 fibers bundle with closely packaged distribution



(b)9 fibers bundle with rotation symmetric distribution

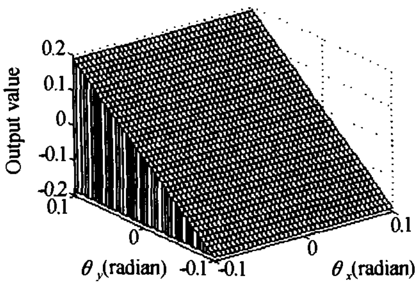
Fig. 5 The cross-section structure of 9 fibers bundle

Fig. 5 (a) shows a closely packed fiber array, in the bundle, the separate distance between source fiber and the 4 near-neighboring fibers is equal to fiber' s diameter D and $\sqrt{2}D$ for the 4 far-neighboring fibers, respectively. Fig. 5 (b) shows a rotation symmetry distribution of receiving fibers cross-section of the 9 fibers bundle and each fiber has same separate distance to the middle light source fiber. For this case, the two-dimensional detecting response functions can be decomposed as two groups of two-dimensional detecting system with angle of 45°.

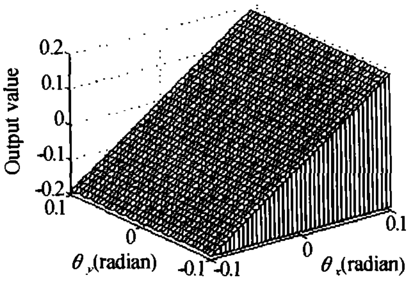
4 Experimental results

The five fiber optic sensing probe fabrication process is as follows: 1) Strapped each fiber end of five fibers; 2) Inserted the five fiber into a frame with the type " + " slot; 3) Fixed the relative position with epoxy; 4) When the epoxy is dried, then inserting the five fiber together into a steel pipe and filling with epoxy again; 5) Finally, polishing the end of five fiber sensing probe and packaging the fiber cable.

For the modulating methods discussed here, the sensor's response characteristic curves are usually obtained by experiments. In previous sections, the functions of the modulating characteristics of the 2-D optical fiber sensor are derived. Equation (18) and (19) are the two independent functions. The computing simulation results of Eq. (18), (19) and (20) are given in Fig. 6 and Fig. 7 with the reflective mirror rotation angles changing range from −0.1 to +0.1 radian.

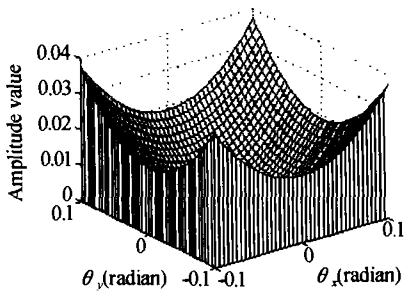


(a)Real part output value vs.the angle θ_x and θ_y

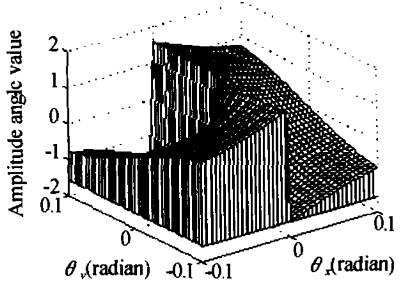


(b)Imaginary part output value vs.the angle θ_x and θ_y

Fig. 6 Simulation results of 2D fiber optic sensor's characteristic function real part and imaginary part



(a)Amplitude value vs.the angle θ_x and θ_y



(b)Amplitude angle value vs.the angle θ_x and θ_y

Fig. 7 Simulation results of 2D fiber optic sensor's characteristic function of amplitude value and amplitude angle vs. the angle θ_x and θ_y

To confirm the characteristic functions, the experimental results and theoretical curves coming from the functions are shown in Fig. 8 and Fig. 9. In our experiments, the core radius of the multi-mode optical fiber is $a_0 = 100$ μm, the radius of the fiber $a_f = 150$ μm, the maximum incident angle $\theta_c = 12.3°$. An LED was used as the light source, the wavelength is 0.89 μm, and drive current is 50 mA. In our case, the coefficient $\xi = 0.081$. For the 2-D sensing probe shown in Fig. 1, the parameters are $l = 1.5$ mm, $d = 0.32$ mm. The experimental curves and theoretical curves are shown in Fig. 8. It can be seen that the theoretical curves and the experimental curves conformity well.

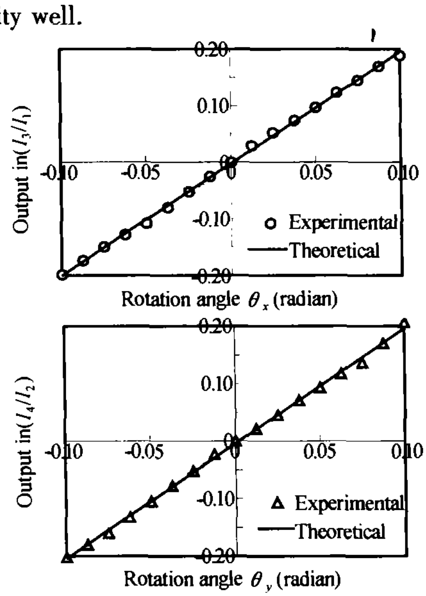
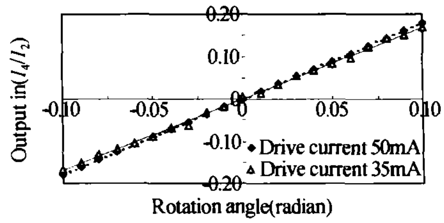
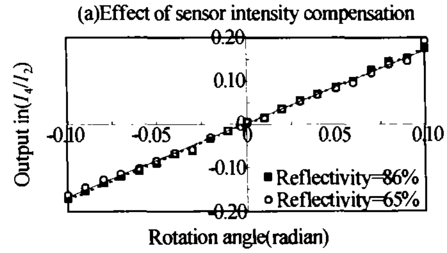


Fig. 8 The experiment results compared with the theoretical curve given by Eq. (16) or (17)



(a)Effect of sensor intensity compensation



(b)Effect of sensor reflectivity compensation

Fig. 9 Compensation results with the changing of the LED drive current and the variation of reflectivity of the mirror

In order to investigate the compensation efficiency of the above sensor, the output signals were tested as the changing of rotation angle of the reflector mirror from −0.1 to +0.1 radian under the different conditions. The effect of the sensor intensity compensation is shown in Fig. 9 (a). The LED source drive current is changed from 50 mA to 35 mA, the value of the variation is 30%, but the output error caused by this change is less then 3%. To check up the effect of the sensing probe reflectivity compensation, two reflectors were used in our experiments. The first one reflectivity is 86%, and the second one is 65%. The change of the reflectivity is about 25%, and the output error caused by the change of reflectivity is less then 1.5% shown in Fig. 9 (b). And the effects of fiber cable bending compensation results are also confirmed in our experiment[2].

5 Conclusions

In this paper, we have introduced a 2-D fiber optic sensing principle and analyzed its compensation characteristics of the 2-D intensity optical fiber reflective sensor. We have also derived the response characteristic functions of the 2-D sensing probe. The results show that, by using the special five-fiber structure of the sensing probe, the sensor is automatically compensated for the variations of light source intensity and for the variations of the reflectivity of reflecting target. Furthermore, if the five fibers are from one cable, the curves and temperature environment of the five fibers could be considered identical, so the losses caused by fiber bends and the variations of losses caused by temperature variations can also be eliminated. For these reason, the using of four receiving fibers in a 2-D intensity modulated optical fiber sensor is an effective and practical way.

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二维光纤传感探头

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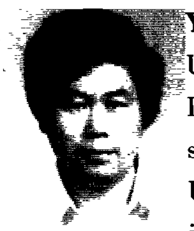
摘 要 给出了一种新颖的二维强度调制反射式光纤传感探头. 导出了二维传感探头的调制函数. 给出了特性调制曲线. 设计并实现了5光纤传感探头. 获得了与理论符合较好的实验结果.

关键词 光纤;特性响应函数;二维光纤传感器;补偿技术



Yuan Libo a professor, was born in 1962 and graduated with a BSc in Physics from Heilongjiang University in 1984 and an M. Eng. in Electrical Engineering from Harbin Shipbuilding Engineering Institute in 1990. He has been invited as a visiting research fellow doing research of fiber optic sensors for smart structure from October 1995 to April 1997 in New Jersey Institute of Technology, USA. He worked on optical waveguide theory, optoelectronic devices and fiber-optic sensors. His interests include fiber optic pressure detecting, temperature probe and fiber optic strain sensors based on white light interferometric techniques. Recently, as principal investigator, he has been involved in a number of NSFC projects on fiber optic sensors for smart structures. Over 120 research papers have been published.