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Simulation and experimental studies of a double-fiber angular displacement sensor

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ABSTRACT

A novel optical fiber angular displacement sensor is reported in this study. It gets the rotating angle of an object by means of the intensity modulation of a reflected light. The sensor probe, which is composed of an emitting fiber and a receiving fiber that are aligned along the vertical direction closely, is fixed directly on the rotating object. The measurements for axial displacement and angular displacement were operated separately. In particular, measurements for angular displacement were performed when the reflector is placed at different distances from the sensor probe separately. There is an excellent linearity between the angular displacement and the sensor output power. The results indicate that the larger the distance between the sensor probe and the reflector, the higher sensitivity the angular displacement sensor has. A theoretical model of the sensor is also developed and the simulate computation demonstrates that the theoretical results are in accordance with the experimental ones. The linear sensing range is ±7.2°, and the maximum sensitivity is 13.71%/deg. Furthermore, the hysteresis and the reproducibility of the measurement of the sensor are investigated. The designed sensor provides a kind of simple and effective method for measuring the angular displacement of a shaft system in practice due to its small size, light weight, good linearity and reproducibility.

1. Introduction

Optical fibers are applied in a wide variety of sensors [1]. One kind of fiber-optic sensors that has been extensively reported in literature is Reflective Intensity Modulated Fiber Optic Sensor (RIM-FOS). The structure of the RIM-FOS was first proposed by W.E. Frank and C.D. Kissinger of the United States [2–4]. The RIM-FOS has become more and more popular in different applications because of the flexibility, the resistance to electromagnetic interference and the simple structure [5,6]. The typical RIM-FOS consists of an emitting fiber (EF), a receiving fiber (RF) and a reflector. The optical fibers are used to transfer the optical signals from an optical source to the measuring field and from there to the signal detection unit like an optical power meter. The received light power is modulated by the parameters to be measured. There have been many reports on a variety of RIM-FOS for axial and lateral displacement measurements [7–11]. Angular displacement measurement has also been achieved by some researchers [13,14] by means of introducing an additional positive lens. However, this kind of measurement needs fine adjustment and enlarges the size of the probe. Sagrario [12] has designed a specific fiber bundle with one emitting fiber and four receiving fibers. Axial and angular displacement can be measured simultaneously, but the angular displacement measurement range is only 40 ± 0.5 mrad. In order to compensate the variation in the light intensity, Shan [15] proposed a differential RIM-FOS for angular displacement measurement and its linear range is ± 6.1°, the sensitivity is also improved. In these researches, the attention focuses on the measurement of the angular rotation of a reflective surface. In this study, the measurement of the angular displacement of the sensor probe is performed, and the influence of the distance between the probe and reflector to the sensor performance is investigated. This sensor was designed for linear response and simplicity. Although the configuration was proposed based on the structure of traditional RIM-FOS, the key difference is that the sensor probe is fixed directly on the rotator intersecting with the rotating shaft. In addition, two optical fibers, which are the receiving fiber and the emitting fiber respectively, are aligned up and down closely in the sensor probe, different to the traditional side-by-side arrangement. In existing reports of this kind of intensity modulated fiber optic angular displacement sensors [12–15], the fiber probe is fixed on the stator and the reflector is fixed on the rotor. For this sensing construction, if the rotating shaft is very thin and the rotating object is very light, such as small torsional pendulum, the reflector will increase the quality and moment of inertia of rotating body, resulting in changes in the state of motion. Our design can avoid this disadvantage because the optical

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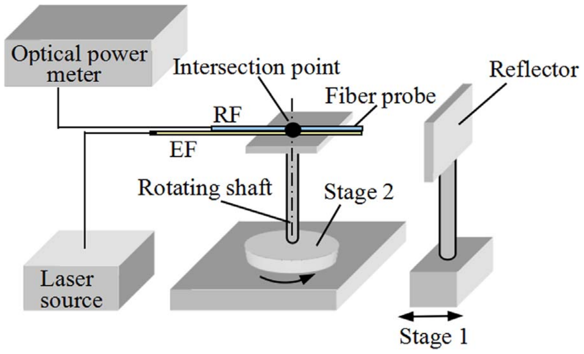

Fig. 1. The experimental configuration of a double-fiber angular displacement sensor. The sensor probe consists of two multimode optical fibers aligned along the vertical direction. It lies on the shaft of stage 2 and can rotate in front of a reflector, which also may move along the horizontal direction with stage 1.

fiber is very light and the impact on the rotating body is very small. In addition, compared with traditional intensity modulated angle sensor which is suitable for reflective surface angle measurement, the designed sensor is more suitable for the angular displacement measurement of shaft systems in opto-mechatronics. The designed sensor has the advantages of small size, light weight, good linearity and reproducibility, and it has little influence on the object under test.

2. Sensor structure and modeling

The configuration of the proposed sensor is shown in Fig. 1. A high stability laser diode controller with a peak wavelength of 1550 nm is used as the light source. The received light power is detected by an optical power meter with a minimum resolution of 0.01 nW. The sensor probe, which is composed of an emitting fiber and a receiving fiber that are aligned up and down closely, is fixed directly on the rotating object intersecting with the rotating shaft. The axial displacement is produced by adjusting the stage 1 while stage 2 is fixed to keep the end face of the sensor probe parallel to the reflector. The angular displacement is produced by controlling the stage 2 while stage 1 is fixed at certain position.

The principle of this kind of intensity modulated fiber optic sensors lies in correlating the light intensity received by the RF to the movement of the probe end face caused by the angular or axial displacement. The expression for the radial intensity profile of the light emitted from the EF can be approximated as having a modified Gaussian profile [16,17], i.e.

$$I(\rho, z) = \frac{P_0}{\pi\cdot\omega^2(z)}\cdot\exp\left[-\frac{\rho^2}{\omega^2(z)}\right] \tag{1}$$

where ρ is the radial distance from the central axis, z is the position along the central axis of the light beam, I_0 is the total power of the emitting light and ω (z) is the effective radius of the beam waist at a specific position z given by

$$\omega(z) = a_{EF} + \zeta\cdot a_{EF}^{1/2}\cdot\tan(arcsinNA)\cdot z^{3/2} = a_{EF} + \eta\cdot\tan(arcsinNA)\cdot z^{3/2} \tag{2}$$

where $\eta = (\zeta\cdot a_{EF}^{1/2})$ is the optical coupling coefficient (in $mm^{-1/2}$), used to characterize the property of the light source and the influence of the EF on the light intensity, can be obtained by experiment, NA is the numerical aperture of the EF.

In order to calculate the light power received by the RF, the position coordinates of the RF in the light field emitted by the virtual EF at an image plane behind the reflector need to be calculated first. A top view of the geometric relationships is presented in Fig. 2. The point A (or B), represented by the position coordinates (ρ, z), is the center of the fiber cross section in the light field. Point C refers to the center of the cross section of the virtual EF. The fiber probe presented by the dotted line represents the position of 0°. It should be noted that in order to make sure the end face of the sensor probe is within the light cone emitted by the virtual EF, the angular displacement θ need to meet the condition $\theta < \arcsin NA$.

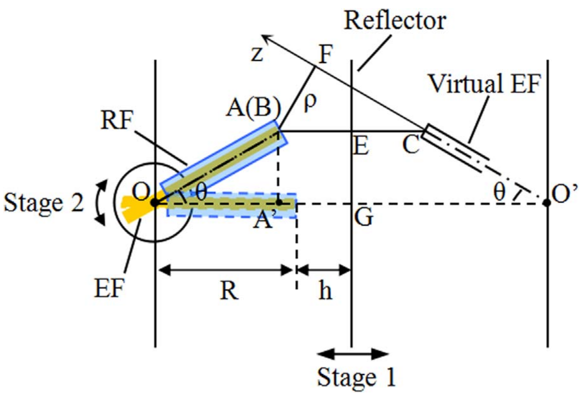

Fig. 2. A top view of the geometric relationships of the sensor. Stage 2 is fixed to make the fiber probe OA (B) vertical to reflector EG when used as axial displacement sensor, and stage 1 is fixed at a certain value of h when used as angular displacement sensor.

As shown in Fig. 2, when θ is zero, the end face of the sensor probe is parallel to the reflector. The distance between the end face of the probe and the reflector is denoted by h. The length from the axis of rotation to the end face of the probe is recorded as the radius of gyration R, which can be presented by $\overline{OA}$. Once the sensor probe is fixed, the value of R is settled. In this study, the value of R is set to be 25 mm. We use $\overline{AB}$ to describe the distance between the center points of the EF and RF which is determined by the fiber diameters $(f_d)_E$ and $(f_d)_R$. The geometric relationships can be written as

$$\overline{OA} = R, \quad \overline{AB} = p = \tfrac{1}{2}(f_d)_E + \tfrac{1}{2}(f_d)_R,$$

$$\overline{OA'} = R\cdot\cos(\theta), \quad \overline{AE} = \overline{A'G} = R + h - R\cdot\cos(\theta) = h + R \cdot[1 - \cos(\theta)],$$

$$\overline{AC} = 2\overline{AE}, \quad \overline{FC} = \overline{AC}\cdot\cos(\theta), \quad \overline{AF} = \overline{AC}\cdot\sin(\theta),$$

$$\overline{BF} = \sqrt{(\overline{AF})^2 + (\overline{AB})^2},$$

$$z_{EF} = z_{RF} = \overline{FC} = 2\{h + R\cdot[1 - cos(\theta)]\}\cdot cos(\theta),$$

$$\rho_{EF} = \overline{AF} = 2\{h + R\cdot[1 - cos(\theta)]\}\cdot sin(\theta),$$

$$\rho_{RF} = \overline{BF} = \sqrt{4\{h + R\cdot[1 - cos(\theta)]\}^2\cdot\sin^2(\theta) + [\tfrac{1}{2}(f_d)_E + \tfrac{1}{2}(f_d)_R]^2}$$

Thus, the position coordinates of the EF and the RF can be written as (ρ_{EF}, z_{EF}) and (ρ_{RF}, z_{RF}). The total light power received by the RF is an integration of the light intensity over the finite light receiving area of the multimode RF core. In order to simplify the calculations, and considering the core area of the RF is very small, the light intensity at the central point of the RF is used as the average light intensity for the whole effective receiving area. The expression can be written as

$$\text{Power=Light intensity} \times \text{Effective receiving area} \times K \tag{3}$$

Where K is the power loss caused by the RF, and the effective receiving area is gained by converting the end face of the RF into a surface parallel to the end face of the virtual EF which can be calculated by

$$S_{eff} = \pi\cdot[(f_d)_R\cdot\cos(2\theta)/2]^2 \tag{4}$$

Therefore, the total power received by the RF can be calculated as

$$P_R = I(\rho_{RF}, z_{RF}) \times S_{eff.} \times K = \frac{K\cdot P_0\cdot S_{eff.}}{\pi\cdot\omega^2(z_{RF})} \times \exp\left[-\frac{\rho_{RF}^2}{\omega^2(z_{RF})}\right] \tag{5}$$

The relationship between the position of the RF and the sensor output power can be described by substituting the position coordinates (ρ_{RF}, z_{RF}) into Eq. (5). There are two variables which are h and θ in the final expression. When the sensor probe is parallel to the reflector, θ is