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Development of a two-dimensional fiber optic position sensor

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ABSTRACT

In this paper, we describe a two-dimensional (2-D) fiber optic position sensor that utilizes the simultaneous measurement of the change in intensity and centroid of image on CCD camera. Both axial and lateral position change can be measured by using this technique. Axial position change is inferred by the change in peak intensity at the CCD camera and lateral position change in centroid of image spot at CCD camera. In the given system, the pitch of the fiber array determines the resolution of lateral position and the sensitivity of axial position is decided by the diameter of optical fiber. This system can be used for position measurement in a 2-D plane for structural health monitoring, alignment monitoring of shafts etc. where the non-contact measurement is needed.

1. Introduction

In recent years, optical fiber position sensors have gained more interest due to non-contact measurement capability, high detection speed and abilities to be used in the environments that suffer from electromagnetic and nuclear radiations where the use of conventional electronic systems is difficult [1,2]. Optical fibers can measure the position by utilizing the various principles such as modulation of intensity, phase, polarization, wavelength, or transit time of light in the fiber [2,3]. Among the above-mentioned sensing principles, intensity modulation based optical fiber sensors are simple and cost effective. The sensors that directly transform the measurands to the variation of light intensity on the receiving fiber are intensity-based sensors. Intensity-based sensors can be distinguished as intrinsic or extrinsic. In the intrinsic sensor, the measurand modulates the transmission properties of the sensing fiber whereas in extrinsic sensors modulation takes place outside the fiber [4]. Extrinsic intensity-based optical fiber sensors generally have two configurations: transmission and reflective based sensors. In the transmission-based sensors, two fibers face each other at a certain distance, while in the reflection- based sensors; one or more fiber transmits the light to a reflecting target while the other collects the light reflected from the target based on different configurations. In both the above-mentioned sensing techniques, optical fibers connected with the light source and detector is known as transmitting and receiving fiber respectively [2,5–8].

In general, most of the transmission type optical fiber position sensors utilize the single fiber-to-fiber light coupling [9], where the light is transmitted from one fiber to other with a known gap between two fibers and output of receiving fiber is coupled to the photodiode. This position is considered as the reference position where the maximum intensity is achieved at the detector. As the position of receiving fiber changes, due to the external factors or measurand quantity, the intensity at the output changes leading to the output intensity variation which is finally interpreted to infer the position change along one-dimension. Jason et al. has reported a one-dimension position measurement technique utilizing the light coupling between single fiber to linear fiber array [10].

However, in this paper, we describe a similar configuration for 2-D position measurement along the two perpendicular directions. In our measurement technique, the output of the sensor is analysed based on the image obtained at CCD camera. Axial position

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change is inferred from the change in the peak intensity and lateral position change is inferred from the change in the centroid of image on CCD camera. The above-mentioned technique can be used for position and alignment monitoring, vibration sensing, crack monitoring, structural health monitoring etc. The paper is divided into following sections. Section 2 gives the principle of operation of an intensity and centroid based position sensor considering the light coupling from the single fiber to linear optical fiber array. Section 3 gives the experimental setup of sensor system, including the algorithm for the 2-D position measurement by finding the peak intensity and centroid of images. Section 4 describes the calibration and the experimental results are discussed. Section 5 gives the conclusion of the paper.

2. Principle of operation of sensor

The transmission based sensors work on the change of position between ends of transmitting and receiving fiber [9,10]. Consider the optical sensor structure as shown in Fig. 1. Let P_e be the optical power of light emitted from the transmitting fiber and P_r is the optical power received by the receiving fiber. Here, the fibers have the same diameter d and θ is the acceptance angle related to the half-light cone. Let the distance between both fiber be x. The collected light depends on the optical power at the receiving fiber that in turn depends on the distance between both fiber tips x and on the light cone angle θ. The emitted light cone, having the vertex inside the transmitting fiber, is called as Emission Cone as shown in Fig. 1. The NA (Numerical Aperture) of the fiber is given as:

$$NA = \sin\theta \tag{1}$$

Let w is the radius of the circular cross section corresponding to the light cone at the receiving fiber. Then,

$$w = (a + x) \times \tan\theta \tag{2}$$

$$w = (a + x) \times \tan(\sin^{-1}(NA)) \tag{3}$$

Considering that the illumination I is constant over the entire surface of the receiving fiber, the collected power by the receiving fiber can be obtained multiplying the corresponding illuminated area S of receiving fiber and the illumination value evaluated at the fiber centre. So,

$$P_r(x) = S \times I(x) \tag{4}$$

$$P_r(x) = \pi\left(\frac{d}{2}\right)^2 \times \frac{P_e}{\pi\omega^2} \tag{5}$$

$$P_r(x) = \frac{\left(\frac{d}{2}\right)^2 \times P_e}{((a + x) \times \tan\theta)^2} \tag{6}$$

Since from the Fig. 1,

$$a = \frac{\left(\frac{d}{2}\right)}{\tan\theta}$$

From Eq. (6) we get, when $x = 0$, received power is equal to transmitted power.

The sensitivity of the sensor with the change in position is given by,

$$\frac{dP_r}{dx} = \frac{2\left(\frac{d}{2}\right)^2 \times P_e}{(\tan\theta)^2 \times (a + x)^3} \tag{7}$$

We can note that position sensitivity is inversely proportional to the cube of distance between the fibers and directly proportional to the square of diameter of fiber. So, transmitting and receiving fiber should be placed as close as possible and cross-sectional diameter should be more. From the Eq. (6), we conclude that when the fiber tips are in contact, the received power is equal to the transmitted power. Otherwise, when there is a gap between the fiber tips, the ratio Pr/Pe decreases as the inverse of the square of the

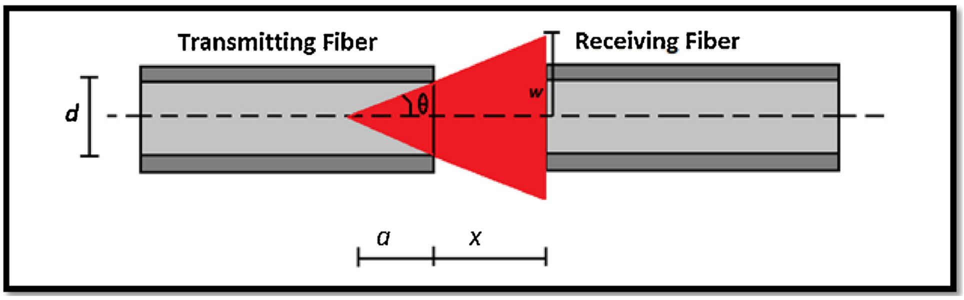

Fig. 1. Schematic of the optical sensor arranged in transmission mode.