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Fiber optic displacement measurement model based on finite reflective surface

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ABSTRACT

We present a fiber optic displacement measurement model based on finite reflective plate. The theoretical model was derived, and simulation analysis of light intensity distribution, reflective plate width, and the distance between fiber probe and reflective plate were conducted in details. The three dimensional received light intensity distribution and the characteristic curve of light intensity were studied as functions of displacement of finite reflective plate. Experiments were carried out to verify the established model. The physical fundamentals and the effect of operating parameters on measuring system performance were revealed in the end.

1. Introduction

Displacement measurement sensors are the core components of advanced instruments. The capacitive displacement sensor is a kind of non-contact sensor and has ultra-high-resolution down to 0.01 nm [1]. However, it has a limited measurement range and high cost while it is hard to meet its high-level application requirements. The inductive displacement sensor has long measuring range with accuracy up to 0.1 μm, and its dynamic characteristics are not so high comparatively [2]. Laser interference displacement sensor has large measurement range and high accuracy of nanometer level, as well as the ability of measuring linear and angular displacement at the same time. However it is too complex and expensive and it would be difficult to meet stringent environmental requirements [3]. Grating displacement sensor utilizes moire fringes to measure in-plane displacement with large measuring range and high accuracy of 5 μm [4]. By contrast, both dial gauge and encoder are medium accuracy, low-cost and widely applied.

Recently fiber optic sensors are applied in many kinds of measurement and control systems, such as industry, medicine, military, aerospace, etc. Fiber optic has many advantages of extremely simple structure, low fabrication cost, high sensitivity, high resistance to electromagnetic interference, and it is suitable for many harsh environments [5,6]. The reflective optical fiber sensors utilize modulation of reflected light intensity to measure displacement [7–10], which have very simple structure and large measurement range. An inclined two fiber displacement sensor is also presented [11], with the dependences of performance metrics reported. Another kind of optical fiber sensor makes use of intensity modulation of transmitted light [12]. Fiber Bragg grating based sensors, which adopt wavelength modulation, are widely used for displacement measurement [13,14]. Fiber optic Sagnac interferometer uses light phase modulation to measure displacement, but its structure is complex [15]. Nowadays great attention is focused on the fiber optic displacement sensors (FODS) based on reflected light modulation.

It is important to establish and analyze the theoretical model of reflective fiber optic sensors to provide theoretical basis for design. Most existing reflective fiber optic sensors are based on large enough reflective planes, especially in fiber optic distance measurement sensors [9–11]. Furthermore, there are also needs for fiber optic sensors with finite reflective surface to measure displacement. A bent-tip optical fiber sensor based on finite reflective surface is developed for soft tissue investigation during minimally invasive surgery [16]. The sensor measures the shift of the finite flat reflector to sense the force, which investigate mechanical soft tissue properties. And a reflective intensity modulated optical fiber sensor is presented to measure rotation axis transverse displacements [17], which also utilizes finite reflector. However, existing fiber optic displacement measurement models have many approximate conditions, and most of them only analyze the size of received light intensity instead of the three-dimensional distribution.

The accurate analysis of reflective fiber optic sensors based on finite reflective surface is theoretical basis for the design and establishment of sensors and systems, in which the reflective surface needs to be finite. The theoretical analysis is helpful to fix the

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parameters of fiber optics, which improves the performance of fiber optics displacement measurement sensors. Therefore a fiber optic displacement measurement model based on finite reflective surface is proposed in this work. The mathematical model is setup while the theoretical analysis and simulation with various illustrative examples for the corresponding model are performed. The three dimensional light intensity distribution and the characteristic curve of light intensity were studied as functions of displacement of finite reflective plate. Experiments are carried out to verify the established model. Further analysis of light intensity modulation, which will change with the measurement system parameters, is conducted at the end.

2. Theoretical model

2.1. Measuring principle

The measuring principle is shown in Fig. 1. The measurement system includes some important components, such as light source, transmitting fiber, receiving fiber, finite reflective plate, and optical power meter. The transmitting and receiving fibers constitute a fiber optic probe, with a certain angle between every fiber and the probe's central axis. The finite reflective plate is a long strip, which is long enough in its length direction and finite in width direction with respect to the diameter of optical fiber. The light is emitted for the source and transmitted into the transmitting fiber. After emitted from the fiber end, the light is reflected by the finite reflective plate and coupled into the receiving fiber. Then the reflected light intensity is detected by the optical power meter. When the finite reflective surface moves in the vertical and lateral directions, the receiving light intensity will be modulated and change accordingly, which can be used for measuring distance and displacement. In this work, displacement refers to the lateral movement of the reflective surface, and distance is the longitudinal movement between the fibers and the reflective surface.

Normally, light exits an end-emitter fiber in a hypothetical cone of light defined by the numerical aperture (NA) of the fiber, and every light point on the end face of transmitting fiber brings about a local light cone which would be combined to form the whole emitting light [18]. The light intensity distribution on the end face of transmitting fiber is considered as Gauss distribution, as well as the light intensity distribution on every section of local light cone. It is supposed that the light travels in straight lines and specular reflection occurs on the reflective surface. Only a part of light is reflected into the receiving fiber and transformed in electric signal.

2.2. Mathematical modeling

The fiber optic sensing system is composed of a fiber optic probe and a rectangular finite reflective plate as shown in Fig. 2(a), and the transmitting fiber Φ and receiving fiber Ψ constitute a

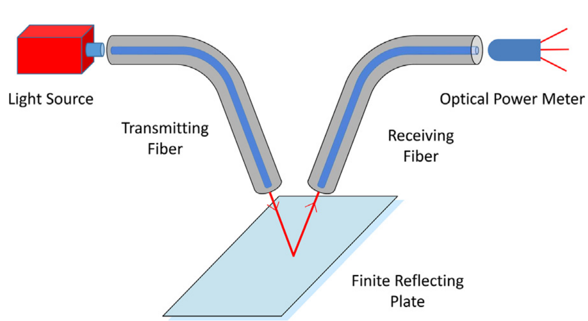

Fig. 1. Principle of measurement system.

fiber optic probe. As shown in Fig. 2(b), the angle between fibers and vertical axis is α, and the horizontal distance between the center points O_T and O_R on the end face of fibers is S. The core radii of fibers with same numerical aperture NA, are R_t and R_r respectively. The reflective plate P has finite size in width direction and rectangular shape, and is placed horizontally below the fiber optic probe. The width direction is parallel to the plane formed by the center axes of fibers. Due to the finite width l of reflecting plate, it may occur that a certain amount of transmitting light cannot be reflected back into the receiving fiber. The distance between the reflective plate P and the center point O_T on the end face of fiber is h, and the distance between the center line along the length direction of reflective plate P and the center point O is d_{PT}.

In this model, the cone angle of transmitted light θ is determined by NA, $\theta = \arcsin(\text{NA})$. The end face of transmitting fiber Φ can be denoted as $\odot O_T$. Every point on $\odot O_T$ forms a normal light cone, and all light emitted from the emitting point is within the normal cone [18]. The light intensity distribution on the plane of receiving fiber Ψ is a linear superposition of all light cones reflected on the finite plate P from all emitting points on the end face of transmitting fiber Φ. The theoretical light intensity which is the most important physical parameter for fiber optic sensing, can be calculated from the mathematical model.

Based on the law of reflection the reflected light is coupled into the receiving fiber Ψ. Here the mirror image Ψ' of receiving fiber is used to substitute for the receiving fiber Ψ, so the light reflection can be transformed into the linear transmission of light, which is easier for the further processing of mathematical model. The infinite plane passing through the end face of the mirror image Ψ', is labeled as Q.

The flow chart of the whole mathematical calculation is shown in Fig. 3. Specific calculation process is presented as follows.

Step 1, establish two coordinate systems, as shown in the Fig. 2 (b),(c). O_T, O_R *and* O_P are the centers of the end faces of fibers and the reflective plate P, respectively. In the front view there is a coordinate system named XO_PY, with origin O_P, X axis along the width direction of plate P and Y axis in the vertical direction of plate P. In the perspective view on the plane opposite the end face of the receiving fiber, set another coordinate system named xO_Ty, with origin O_T, x axis in the width direction of plate P, y axis being parallel to plate P.

Step 2, choose a point B randomly as an initialized point.

Step 3, calculate its light intensity. Choose a random emitting point B on the end face of the transmitting fiber, whose coordinates are (x_B, y_B). The light intensity follows a Gaussian distribution, consequently the light intensity at point B can be calculated as follows:

$$I(x_B, y_B) = \frac{2\eta P_0}{\pi\omega_0{}^2} \exp\left[-\frac{2\left(x_B{}^2 + y_B{}^2\right)}{\omega_0{}^2}\right] \tag{1}$$

where P_0 is the power of light source, η is the transmission efficiency of transmitting fiber, ω_0 is the Gauss width at 1/e peak value. Because the distance between the transmitting fiber and the mirror image of receiving fiber is smaller than Rayleigh Range, we set Gauss width equal to the radius of fiber, namely $\omega_0 = R_t$ [10].

Step 4, analyze the intensity distribution of point B formed on the end face of receiving fiber.

Step 4.1, due to the finite reflective surface of finite width and infinite length, one part of the light cone from point B reaches the reflective plate and is reflected into the end face of the receiving fiber, while the other part cannot reach the end face of fiber, therefore it doesn't participate in the calculation of light intensity distribution (LID).

Step 4.2, calculate the region $R_{B\text{-}Q}$ of the light spot on the plate Q, which is formed by the light cone from the emitting point B. The