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Real-time non-contact optical detection system for roller deformation based on artificial neural network

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ABSTRACT

A non-contact real-time optical fiber measurement system for roller deformation is designed based on the principle of reflective displacement fiber-optic sensor. The theory and mathematical model of the sensor are deduced in detail. By using a novel probe of three optical fibers with equal transverse space, the effects of fluctuations in light source, reflective changing of target surface and the light intensity losses in fiber lines are automatically compensated. Meantime, an optical fiber sensor model of linearizing output signal and correcting static error based on artificial neural network (ANN) is set up. By using interpolation method and value filtering to process the signals based on ANN, the influence of random noise and the vibration of roller bearing can be reduced effectively. Therefore the *linearity*, accuracy and resolution are enhanced remarkably. Experimental results proved the accuracy of the system could reach to the demand of practical production process. It provides a new method for high speed, accurate and real-time detection of roller deformation.

1. Introduction

Roller plays an important role in rolling mill. Its working state will affect the quality of the rolling products directly. After long time working, the surface of a roller will deform. Therefore the shape of the roller surface will change and result in difficult controlling the thickness of rolling boards [1,2]. Furthermore it can lead to the decline of the product quality of a rolling mill. Therefore it is very urgent to detect the roller deformation exactly and real time [3,4]. In previous studies, researchers have tested a lot of methods, which had achieved lots of important results, such as magnetic flaw detection, color flaw detection, ultrasonic flaw detection [5–8]. However, domestic rollers deformation detection systems are still dominated by imported products for various reasons. In this paper a real-time detection method using a reflective displacement fiber-optic sensor is put forward. Meantime by using ANN to process the output signals of the sensor, a better linearity and lager measurement range can be gained. Moreover the stability and precision can be enhanced. This detection system can also been connected with computer to realize intelligent controlling easily. A simulation-software program is compiled with Microsoft Visual Basic 6.0 based on this detection principle. By using it, the detection curves are automatically drawn and the data of I/O signals of this system can be gained in real time.

2. Theory

2.1. Principle and mathematic model of optical fiber sensor

The system of our design is based on the technique of fiber-optic reflective displacement sensor. In general it consists of a fiber as a light source (TF) and the other as a light receiver (RF) [9–11]. The structure can be seen in Fig. 1(a).

We use light intensity modulation function M to describe the detection theory as seen in Eq. (1).

$$M = \frac{P_r}{P_t} = \frac{\Phi_r}{\Phi_t} = \delta \frac{S_r}{S} \tag{1}$$

P_r is receiving power of RF, P_t is the transmitting power of TR, Φ_r is the receiving luminous flux of RF, Φ_t is the transmitting luminous flux of TR, S_r is the magnitude of effective receiving area of RF, S is the facula area in $2d$ distance to the image of TF, and δ is the factor related to the characteristic of reflecting surface. The geometric figure can be seen in Fig. 1(b). We can calculate the magnitude of effective receiving area of RF in detail, according to the changing of

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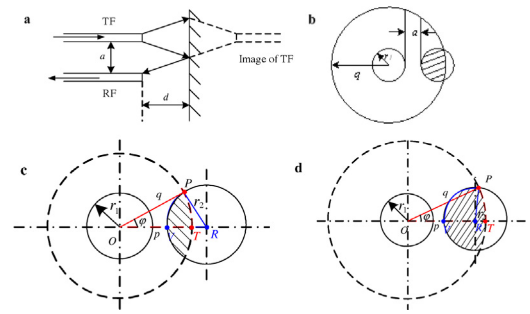

Fig. 1. (a) Structure of optical sensor; (b) geometric figure of the light path; (c) geometric analysis of light path when $q > p - r_2$; (d) geometric analysis of light path when $q \le p - r_2$.

distance d. The radius of the facula in $2d$ distance to the image of TF q can be got in Fig. 1(c) and (d).

$$q = 2d \tan\theta_N + r_1 \tag{2}$$

where θ_N is the angle of numerical aperture (NA) ($NA = \sin\theta_N$), $r_{1,2}$ are the radiuses of TF and RF respectively, d is the displacement from the end face of the probe to the reflective surface, $NA_{1,2}$ are the numerical apertures of TF and RF respectively (in general $NA_1 = NA_2$, and p is the distance between the axis of two optical fibers.)

(2) If $p - r_2 < q \le (p^2 + {r_2}^2)^{1/2}$, effective receiving light of RF is the shaded area in Fig. 2(c). By analyzing the geometrical relationship, we can get

$$\varphi = \cos^{-1}\frac{p^2 + q^2 - r_2^2}{2pq} \tag{4}$$

The effective receiving light of RF is

$$S_r = 2[\mathrm{Area}(OPT) + \mathrm{Area}(RPV) - \mathrm{Area}(OPR)] \tag{5}$$

$$S_r = \varphi q^2 + \sin^{-1}\left(\frac{q\sin\varphi}{r_2}\right)\cdot r_2^2 - pq\sin\varphi \tag{6}$$

(3) If $(p^2 + r_2^2)^{1/2} < q \le p + r_2$, effective receiving light of RF is just the shaded area, so

$$\varphi = \cos^{-1}\frac{p^2 + q^2 - r_2^2}{2pq} \tag{7}$$

$$S_r = \varphi q^2 + \left[\pi - \sin^{-1}\left(\frac{q\sin\varphi}{r_2}\right)\right]\cdot r_2^2 - pq\sin\varphi \tag{8}$$

(4) if $q > p + r_2$, the whole receiving end face of RF is in the illuminating area of the transmitting light, so now effective receiving area is

$$S_r = \pi r_2^2 \tag{9}$$

According to the above analyses of the effective receiving area, the light intensity modulation function M can be written as

$$M = \begin{cases} 0 & d \le \dfrac{p - r_1 - r_2}{2\tan\theta_N} \\ \delta\dfrac{\varphi q^2 + \sin^{-1}(q\sin\varphi/r_2)r_2^2 - pq\sin\varphi}{\pi q^2} & \dfrac{p - r_1 - r_2}{2\tan\theta_N} < d \le \dfrac{(p^2 + r_2^2)^{1/2} - r_1}{2\tan\theta_N} \\ \delta\dfrac{\varphi q^2 + [\pi - \sin^{-1}(q\sin\varphi/r_2)]r_2^2 - pq\sin\varphi}{\pi q^2} & \dfrac{(p^2 + r_2^2)^{1/2} - r_1}{2\tan\theta_N} < d \le \dfrac{p - r_1 + r_2}{2\tan\theta_N} \\ \delta\cdot(r_2/q)^2 & d > \dfrac{p - r_1 + r_2}{2\tan\theta_N} \end{cases} \tag{10}$$

According to the magnitude of q, there are several situations as follow:

(1) If $q \le p - r_2$, the light transmitting by the image of TF can not illuminate RF, we get

$$S_r = 0 \tag{3}$$

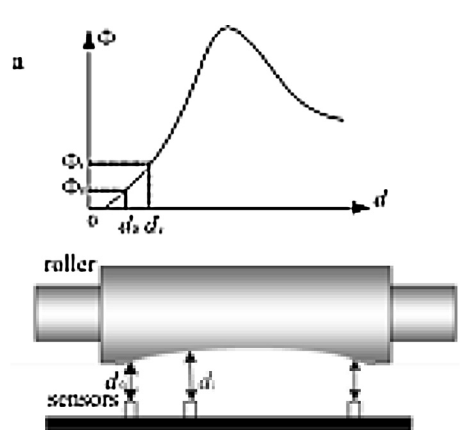

Fig. 2. Principle of the detection method.

2.2. Detection theory and optics detection system modeling

When TF illuminates the reflecting surface, RF can receive the reflected light. If the roller deformed, the displacement between the probe and the surface of the roller will change. Therefore the light received by RF is also changed and Φ of RF is changed with it. By measuring Φ of the RF, we can determine the deformation of the roller by processing these displacement data precisely as shown in Fig. 2.

We modified the traditional optical fiber probe and used a novel optical fiber probe to proceed the detection. One optical fiber is used as TR and the other two are used as FR1 and FR2. We set up the coordinates system shown in Fig. 3. Receiving luminous flux of RF is equivalent to the one that received by the image of RF multiplying by the reflectivity.

According to the light distribution law of optical fiber end face, the receiving luminous flux of RF1 and 2 can be illustrated as Eq. (11).

$$\Phi_{1,2}(r, 2z) = \rho_{1,2}\iint_{s_{1,2}}\frac{K_0 K_{1,2}\Phi_0}{\pi R^2(2z)} \times \exp\Big(-\sum_{i,j}\eta_{i,j}r_{i,j}\Big)\exp\left[\frac{-r^2}{R^2(2z)}\right]ds_{1,2} \tag{11}$$

where Φ_0 is the luminous flux of light source, k_0 the loss in TF, $k_{1,2}$ the loss in the RF1,2, $s_{1,2}$ the receiving fiber core area, $\rho_{1,2}$