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Real-time optical detection system for monitoring roller condition with automatic error compensation

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ABSTRACT

According to the characteristics and the demand of the detection accuracy, an optical detection scheme for monitoring roller condition was proposed and experimentally demonstrated. By analyzing the principle and setting up the mathematical model, a real-time optical detection system is presented in this paper. Moreover error compensation methods of the optical detection part, installation and movement of the detection device, and eccentricity, roundness and rotary movement of the working roller have been adopted in order to ensure the detection process in atrocious condition and to examine roller's shape precisely in real-time. A series of experiments were performed to verify the validity and practical applicability of the detection system. It provides a new method for high speed, accurate and automatic real-time detection for roller condition.

1. Introduction

A roller is a commonly used metallurgical tool and plays a critical role in steel mills. Its working state affects the quality of the rolling products directly. Therefore monitoring the working condition of a roller is of vital importance [1,2].

The influence of continuous working conditions such as cyclic load, drastic surface temperature fluctuation, contact friction between rollers and rolled pieces makes the surface of a roller to wear and the shape of the roller will also change. This results in difficulty in controlling the shape and the thickness of the rolling products. Furthermore it will affect the product quality. After usage for a period of time, rollers should be grinded, repaired or replaced to ensure the product quality [3–7]. Before doing this process, the condition of the roller needs to be inspected and the position and the magnitude of grinding should be decided. Therefore it is very important to detect the roller's wear and shape exactly in time.

One of the conventional methods to solve the problem is to remove the roller and grind it to the standard size, and replace it back to the rolling mill after repair. However, by this method the roller can be inspected only periodically. The repair time is fixed and determined just empirically. Therefore it is hard to know the roller's condition in real time and it will take a long time to replace a roller [8,9]. Due to this the product quality cannot be assured and the production efficiency will be affected.

Previously, many researchers have studied various detection methods such as magnetic flaw detection, color flaw detection, ultrasonic flaw detection, eddy current detection and photoelectricity detection [10–15]. However many detection methods can hardly be carried out on-site, because of the electromagnetic interference, high temperature and harsh working environments of a roller. To date many steel mills still detect the roller's condition manually in a traditional way. Researchers are still working to find effective methods for detecting roller's condition in real-time for automatic on-site detection [16,17].

In addition, many factors may also affect and give errors to the detection system, even causing the roller to breakdown. The high quality of the rolling products demands precision size. Therefore the working conditions of a roller should be monitored and the detection errors should be eliminated to ensure the accuracy of the detection method and the normal working of rollers [18,19].

In this manuscript, we propose an on-site real-time detection system for monitoring roller condition by using a modified fiber-optic sensing probe. By this method, we were able to eliminate the effect of fluctuations in the light source, reflective changing of target surface and the intensity losses in the fiber lines. We also obtained the advantages that were regarded as important by previous studies, such as non-contact, no electromagnetic interference, stability and easy connectivity with computer to realize intelligent control. In addition, the mounting mechanism was

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designed, which makes the sensing probe that scans the roller's surface along the radial direction automatically controlled by a distance controlling part.

One significant improvement in our work is that we are interested in eliminating the common errors, which frequently arose in the roller detection system and reduced the detection precision [20,21]. We have found some valid methods from the aspects of optical detection part, installation and moving mechanism, and working roller itself to compensate the errors and improve the detection accuracy. A high speed software for real time signal processing was also developed and the data could be saved separately, and observed to see if the detection system was working abnormally or whether steps should be taken to conquer it immediately.

Furthermore, in order to use the detection system available on-site, a series of experiments were conducted in the simulated working situation and the validity of detection principle and error compensation methods was verified. Moreover some experiments of environment effect factors have been conducted and some results obtained to make the detection more practical.

2. Theory

In this manuscript, a modulation function M is used to describe the detection efficiency. M is the ratio of Φ_r to Φ_t. Φ_r is the receiving luminous flux of receiving fiber (RF) and Φ_t is the transmitting luminous flux of transmitting fiber (TR). The mathematical model of a modified optical fiber sensor being used in this detection system was deduced from the traditional Y type probe model [22,23].

2.1. Detection principle of roller condition

As shown in Fig. 1(a), the fundamental principle of this system is that the deformation of a roller's surface will make the distance between the probe and the surface of the roller change.

The output luminous flux Φ of RF is a function of the distance from the reflecting target to the probe. When the distance is within a certain range, these two quantities have a good linear relationship [24]. By measuring Φ of the RF, we can determine the displacement between the sensor probe and the reflecting target. A good understandable way can be seen in Fig. 1(b).

The variation of Φ is

$$\Delta\Phi = \Phi_i - \Phi_0 \quad (1)$$

In Eq. (1) Φ_i is the output luminous flux of RF in position d_i, Φ_0 is the output luminous flux of RF in position d_0.

The displacement between the roller's surface and the probe can be considered as

$$\Delta d = d_i - d_0 \quad (2)$$

Therefore detecting the shape of the roller can be detected by processing these displacement data precisely.

2.2. Optical detection system modeling

In this paper a modified optics fiber probe was used instead of the traditional one to precede a new application of the detection for roller shape as stated in our previous work [25,26]. The structure of this kind of fiber-optic sensing probe is shown in Fig. 2(a). By using the central axis of TF as X-coordinates, and the end face of the optical sensor probe as Y-coordinates, the coordination system shown in Fig. 2(b) was set up. A picture of the probe is shown in Fig. 2(c). The receiving luminous flux of RF is equivalent to the one that is received by the image of RF multiplied by the reflectivity.

According to the light distribution law of optical fiber end face [27], the receiving luminous flux is illustrated by

$$\Phi(r,z) = \rho \iint_s KI(r,z)\exp\left(-\sum_i \eta_i r_i\right) ds \quad (3)$$

where ρ is the reflectivity, K is the light power loss coefficient of RF (intrinsic loss), S is the effective receiving area of RF, and $\exp(-\sum_i \eta_i r_i)$ is the bend loss of RF. According to the analysis of the theory and experiments, an expression of bending loss was presented in Refs. [27–29]. It is a realistic and general formula, which uses an exponential expression to describe the bending losses and can calculate the bending loss in light field distribution. Where r is the radius of the light spot, which is a distance z away from the end of the optical, and r_i is the radius of the optical fiber at bending points.

Using the above equation to integrate over each end face of RF1 and 2, the receiving luminous flux of RF1 and 2 can be obtained respectively as

$$\Phi_1(r,2z) = \rho_1 \iint_{s_1} \frac{K_0 K_1 \Phi_0}{\pi R^2(2z)} \exp\left(-\sum_i \eta_i r_i\right) \exp[-r^2/R^2(2z)] ds_1 \quad (4)$$

$$\Phi_2(r,2z) = \rho_2 \iint_{s_2} \frac{K_0 K_2 \Phi_0}{\pi R^2(2z)} \exp\left(-\sum_j \eta_j r_j\right) \exp[-r^2/R^2(2z)] ds_2 \quad (5)$$

where Φ_0 is the luminous flux of light source, K_0 the loss factor in TF, $K_{1,2}$ the loss factor in the RF1 and 2, $s_{1,2}$ the receiving fiber core area, $\rho_{1,2}$ is the reflecting coefficient, $\exp_{1,2}$ the additional losses in the receiving fiber caused by bends, $R(2z)$ the effective radius of output optical field and $R(z) = a_0 + kz^{3/2} \tan \theta_c$, d is the distance

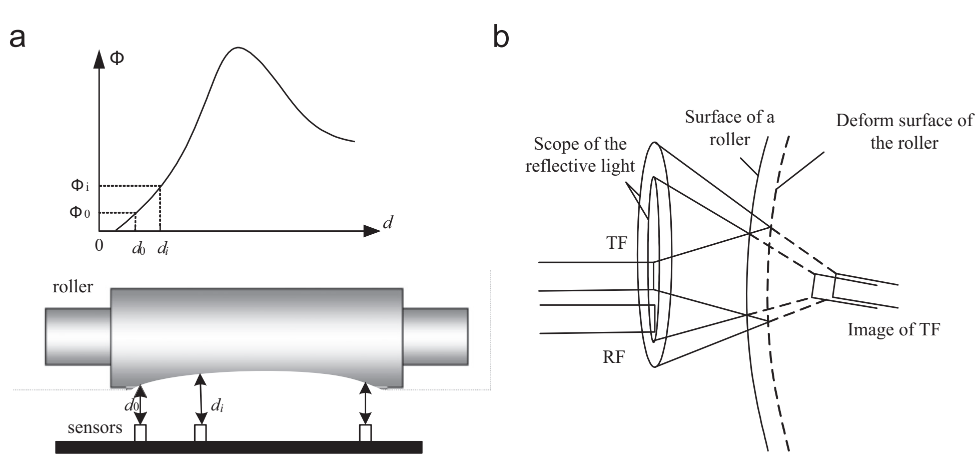

Fig. 1. (a) Principle of the detection method. (b) Theory of optics detection system.