On-line monitoring system for roller wear with axes shift compensation based on laser-linear charge coupled device

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Abstract. Based on the principle of laser-linear array charge-coupled device (CCD) detection technology, a high accuracy nontouch on-line system for monitoring roller wear is brought forward. The principle and composition of the laser-linear array CCD detection system and the operation process were expatiated. Aiming at the errors of the roller's axes shifting during the detection process, compensating steps were adopted from the vertical and the parallel direction to the detection surface. This effectively enhanced the accuracy of the detection system. Experiments proved that the accuracy of the system could reach the demand of the practical production process. It provides a new method for high speed, accuracy, and automatic on-line monitoring of roller wear. r shapegear array CCD detection. A simulation-software program is also compiled based on this principle. By using this program, the I/O signals's data for this system is gained and the detection curves can be drawn automatically. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.52.4.043604]

1 Introduction

The roller is an important metallurgy tool in the rolling mill and the surface of a roller directly affects the quantity of the rolling product. After much use, the roller's surface wears down and its shape changes. This results in the difficulty of controlling the shape and the thickness of a board. Furthermore, it can lead to the decline in the product quality of a rolling mill. Therefore it is very important to detect roller wear exactly in real time. Examining the profile of a working roller between the intervals of rolling is called on-line detection for roller wear.[1,2] The study of on-line detection roller wear is very important for selecting the grinding time, reducing the exchange frequency of rollers, improving the quality of the product, and realizing on-line grinding rollers.[3,4]

In previous studies, researchers have studied many methods that had achieved numerous important results, such as magnetic flaw detection, color flaw detection, and ultrasonic flaw detection.[5–8] However, monitoring systems of roller wear in China are still dominated by imported products for various reasons.[9]

In this paper, after summarizing the experiences of the detection methods inside and outside, we carry on the theoretic and experimental studies of roller wear on-line non-touch monitoring system based on laser-linear array charge-coupled device (CCD) detection technology. Where roller surface has been worn, roller radius is different in different locations. If an incident ray leans to the surface of a worn roller, the angle of the reflected ray will be changed following the difference of the roller radius. Marking down the position of the reflected ray by using CCD, the roller radius can be accurately worked out by geometrical optics. Moreover, an error compensation algorithm is put forward to offset the shift of the roller axis

in this monitoring system. Therefore the stability and the accuracy were improved remarkably.

2 Monitoring Principle

The monitoring principle of laser-linear array CCD technology for roller wear is shown in Fig. 1.

If a roller has been worn, the radius of the roller will be different along the surface of the roller. When an incident ray leans to the surface of the roller, the angle of reflected ray is changed with the radius of the roller.[10,11] Writing down the positions of the reflected ray by CCD, the roller radius can be calculated and the wear of the roller can be obtained. After the surface of a whole roller was scanned by this method, a series of reflected positions are gained on CCD and a group of roller radii is figured out. Combining those data, a curve of the roller wear distribution is built up.

The geometric ray way drawn for calculating the radius of a roller is shown in Fig. 2. As it can be seen, R is the radius of roller, α is the incident angle, L is the distance between the roller center and the CCD detecting surface, S is the displacement of incident ray from the intersection of the roller center and the CCD detecting surface, H is the distance between incident ray and the point of reflected ray on CCD.

We can get L and $\tan 2a$ in Eq. (1) according to Fig. 2.

$$L = \frac{H}{\tan 2\alpha} + \sqrt{R^2 - S^2}, \quad \sin \alpha = \frac{S}{R},$$
$$\tan 2\alpha \frac{2S\sqrt{R^2 - S^2}}{R^2 - 2S^2}. \tag{1}$$

When the detection process begins, the detector moves from one end to the other end of the roller and records
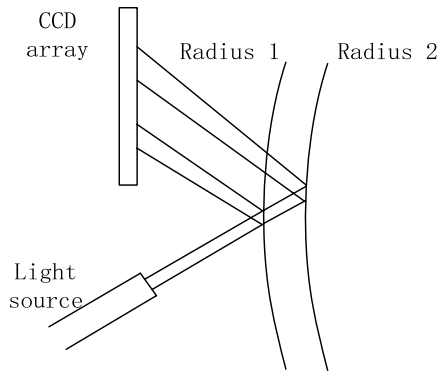
Fig. 1 Principle of CCD monitoring system for roller wear.

the reflected ray on a CCD array. Then the distance between the imaging position in CCD and the light source can be calculated. After much use the roller must be worn and the radius will definitely change. As the parameters of R, L, S, and H will also change with the wear of the roller, so we had better transfer these parameters as variable forms. If we change these constants as variables because of the roller wear, we can get the relationship of the imaging position h on CCD and the radius of the roller r as Eq. (2).

$$h = \frac{2SL\sqrt{r^2 - S^2} - 2S(r^2 - S^2)}{(r^2 - 2S^2)}. \quad (2)$$

By transforming the imaging position on CCD to the radius of the roller, the curve of the radius can be obtained. Therefore the roller wear is detected and the purpose of the monitoring system can be achieved.

3 Composition of the System

A three degree-of-freedom traveling mechanism with optical detection sensors fixed in it that can move along the radial and axial direction of the roller were designed for detecting roller wear on-line. The schematic diagram of the system composition is shown in Fig. 3.

The first and the third sensor fixed on each side of the roller cannot move. They were designed to detect the deliberate ends of the roller. Therefore the deliberate yawp can be eliminated easily. The second sensor driven by a stepping motor and mechanical gearing can scan the surface of the roller in constant speed along the axis direction.

Because the two ends of roller cannot be worn during the process of rolling, roller radius of the two roller ends is
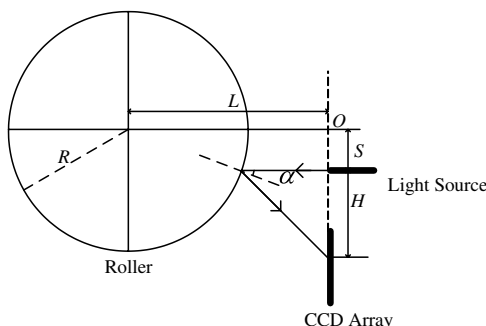

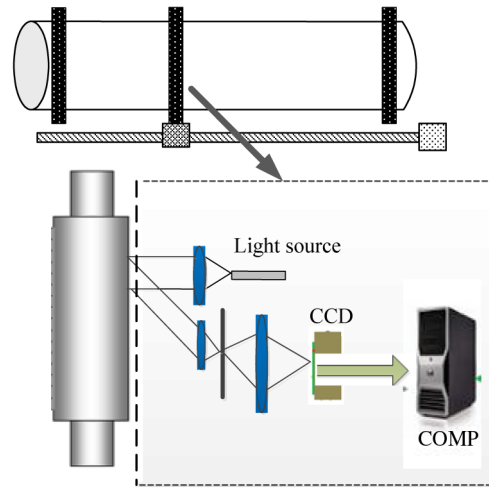**Fig. 2** Geometric ray of detection method.

Fig. 3 Schematic diagram of detective system composition.

always the standard radius. Before detecting, we activate this system from one end of the roller. We then move the detector lightly to find out the original position of the monitoring system (O), where the incident ray vertical irradiates with shifting a distance S, then record the distance between the imaging position of the reflection ray on CCD array and the position of the incident ray. Finally, we calculate the distance between the roller axis and the detector, so the system-initializing operation is finished and all necessary parameters of the measurement are gained.

The flow chart of the monitoring system is shown in Fig. 4 and is composed of four main modules; the monitoring probe, the signal acquisition, system control, and light source. The probe module is in charge of issuing the orders of start, stop, and modulating the position of the probe. The signal acquisition module collects the signals and amplifies the weak light signal output by the probe, then transforming it to a digital signal. The system control module can control the operation of the whole system and communicate with the upper computer. Finally, the light source module is used for providing the steady source of the whole system.

4 Error Compensation for the Shift of Roller Axis

Normally the axis of the roller x will not shift. However, when the roller is working the roller axis may have a small shift. Therefore, it cannot be guaranteed that the roller axis is always at the same direction during measurement. Also, it cannot be guaranteed that the monitoring tracking system is always parallel with the roller axis. Therefore, the geometric relationship of the detection surface and the roller will change. The shift of roller axis can be separated into two directions: vertical and horizontal direction of the detection level. Through analyzing, the error compensation algorithm for the roller axis shift at both directions is put forward. The geometrical relationship of the axes and the lights is shown in Fig. 5.

In Fig. 5, β is the detection surface, x' is the shifted axes of the roller, DP and D_1P_1 are incident rays, PB and P_1B_1 are reflection rays.

The vertical direction shift means the distance changing between the roller axis and the detector. The geometrical relationship is shown in Fig. 6. Through geometric analysis, this kind of shift is related with the change of l. Therefore it
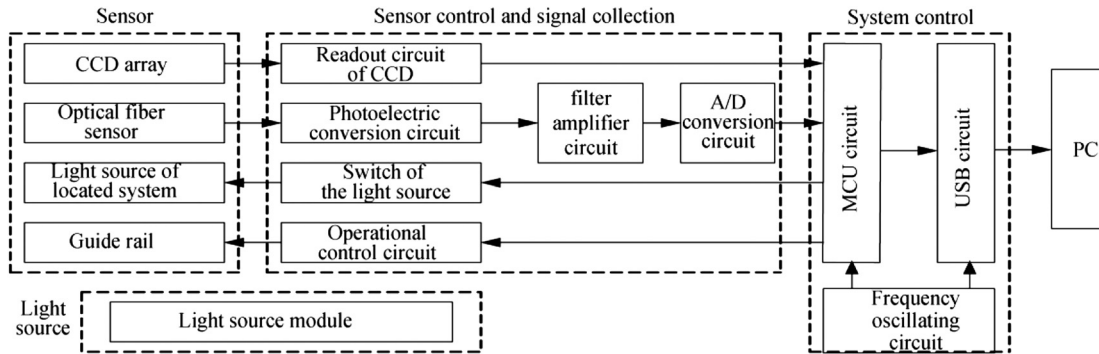
Fig. 4 Flow charts of the monitoring system for roller wear.

can be calculated and compensated by modifying the expression of l.

The magnitude of l between the roller axis and the detector is

$$l = \frac{x}{A}L_1 + \frac{A-x}{A}L_0, \qquad (3)$$

where L_0 is the original distance between the roller axis and the detector before the detecting system works; L_1 is the distance between the roller axis and the detector after the detection completes, A is the length of the roller, x is the moving distance of the detector in any time. The original value and the final value can be recorded when the measurement system is initialized and ended.

The horizontal direction shift means the change of the incident ray shift shown in Fig. 7. Through geometry analysis, it is related with the change of s. The compensation method of s is similar to l. By recording the original value and the end value of s, the shift of the incident ray can be calculated and compensated. The shift of the incident ray needs to be recorded at the end of the detecting process.

The shift distance s between the incident ray and the detection surface is
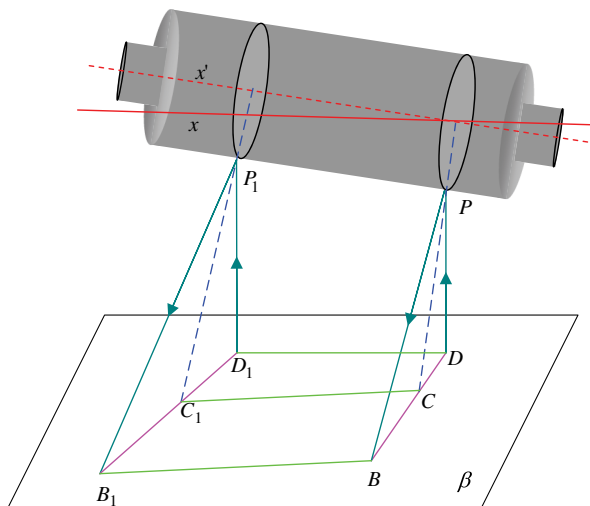
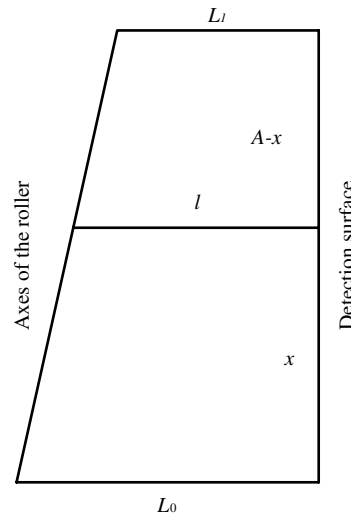$$s = \frac{x}{A}S_1 - \frac{A-x}{A}S_0, \qquad (4)$$

Fig. 6 Vertical direction shift from measurement level.

where S_0 is the shift of incident ray before the detecting system works, S_1 is the shift of incident ray after the detection completes, s is the shift of incident ray.

According to Eqs. (3) and (4), the relationship of the imaging position on CCD and roller wear can be obtained after error compensation in Eq. (5).

$$h = 2\left(\frac{x}{A}S_1 + \frac{A-x}{A}S_0\right)\left(\frac{x}{A}L_1 + \frac{A-x}{A}L_0\right)$$
$$\times \frac{\sqrt{r^2 - \left(\frac{x}{A}S_1 + \frac{A-x}{A}S_0\right)^2} - r^2 + \left(\frac{x}{A}S_1 + \frac{A-x}{A}S_0\right)^2}{r^2 - 2\left(\frac{x}{A}S_1 + \frac{A-x}{A}S_0\right)^2}, \qquad (5)$$

where h is the imaging position on CCD, and r is the radius of the roller.

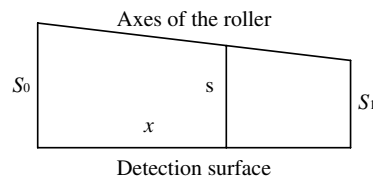**Fig. 5** Geometrical relationship of the axes and the rays.

Fig. 7 Horizontal direction shift from measurement level.

Table 1 Results of CCD monitoring system for roller wear before and after compensation (mm).

Point	Standard h	h_1 Before compensation	$\Delta h_1 = h_1 - h$	h_2 After compensation	$\Delta h_2 = h_2 - h$	Standard r	r_1 Before compensation	$\Delta r_1 = r_1 - r$	r_2 After compensation	$\Delta r_2 = r_2 - r$
0	277.01	278.02	1.01	277.66	0.65	499.00	498.13	−0.87	498.79	−0.21
200	280.64	279.63	−1.01	279.96	−0.68	496.65	495.90	−0.75	496.00	−0.65
500	280.89	279.89	−1.00	280.19	−0.70	496.22	495.57	−0.65	495.97	−0.25
800	281.41	280.40	−1.01	281.64	0.23	495.48	494.58	−0.90	494.90	−0.58
1100	285.21	286.21	1.00	286.01	0.80	494.30	495.10	0.80	494.90	0.60
1400	285.65	286.65	1.00	286.05	0.40	495.11	493.11	−2.00	494.11	−1.00
1700	284.75	285.70	0.95	284.69	−0.06	492.15	491.15	−1.00	491.99	−0.16
2000	279.87	278.87	−1.00	279.58	−0.29	497.71	496.01	−1.70	496.99	−0.72
2300	282.28	281.02	−1.26	281.89	−0.39	494.60	493.60	−1.00	493.79	−0.81
2600	275.56	278.56	3.00	276.06	0.50	498.18	497.18	−1.00	497.98	−0.20

5 Numerical Experiments and Discussion

To verify practicability of the monitoring system for roller wear, simulation software is developed for the system. The simulation interface include the sketch map of the monitoring system, the data display area, and control buttons. After running the program, the curves of h and r can be drawn.

In order to verify the compensation method for shift of the roller axis, we took another experiment and took out 10 detection points randomly. The roller used for experiment is $\oint 1000 \times 2600$, and we assumed $R = 500$ mm, $L = 700$ mm, $S = 100$ mm, $S_0 = 110$ mm, $S_1 = 90$ mm, $L_0 = 710$ mm, $L_1 = 690$ mm, $A = 2600$ mm.

By scanning the whole roller along its axis direction, the data of 10 detection points were obtained and the results were filled in Table 1.

As it can be seen clearly from the table, after using the compensation method the detection data is much closer to the standard data and the error of h and r became smaller. Therefore the compensation method is feasible.

According to the different radius of the worn roller at a different position, the array of different reflection positions can be gained on CCD. By using Eqs. (1) through (5), the radius of the roller can be calculated. Running the simulation program we can draw the curves of r and h in Fig. 8.

Notably through comparing, the change of h is larger than the change of r. By using this method, it is easy to detect the big change of h and we can calculate the small change of r more accurately. Thus, the practicability of this monitoring system for roller wear is demonstrated.

To verify the accuracy of this measurement system, we also simulated the curves before and after the compensation method. The experimental date of r and of h were analyzed and compared by drawing their curves of three situations by the simulation software in Fig. 9.
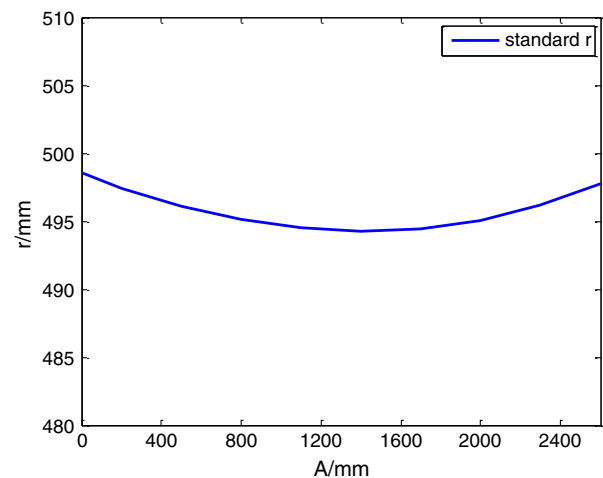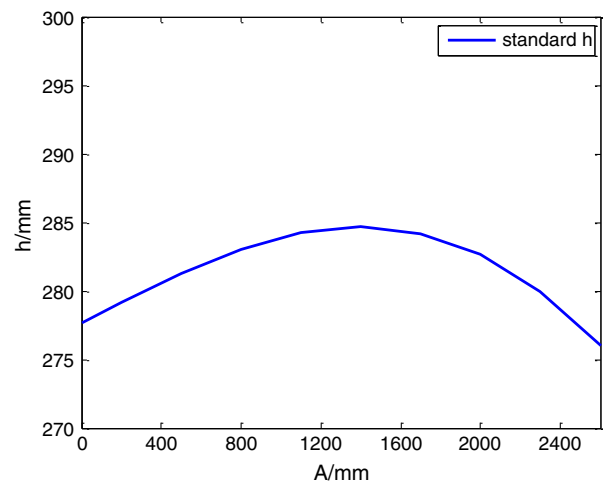
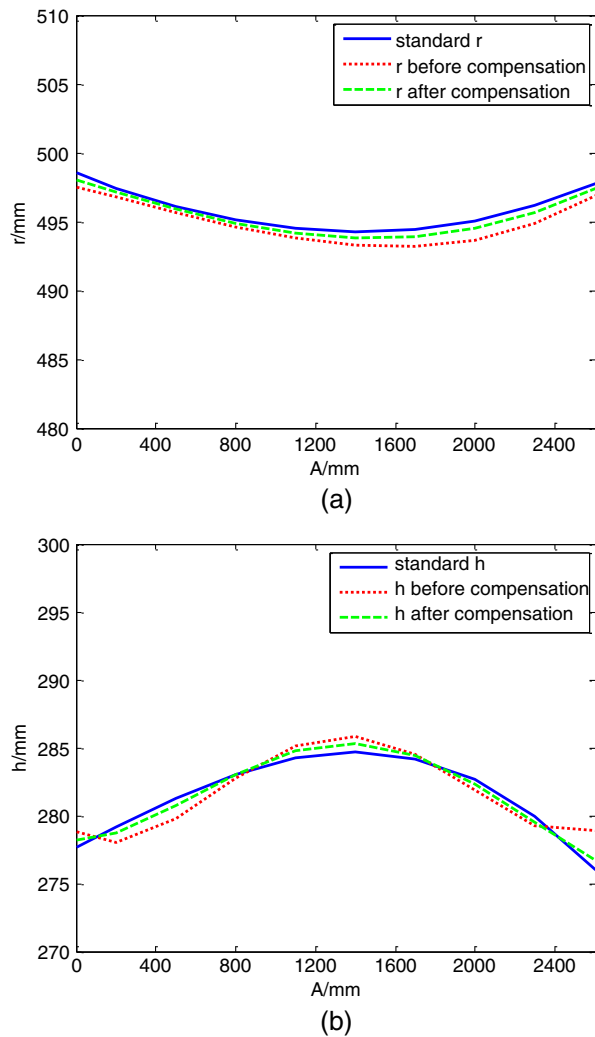**Fig. 8** (a) Detection curve r. (b) Detection curve h.

Fig. 9 (a) Curves r before and after compensation. (b) Curves h before and after compensation.

We find in Fig. 9 that the curves of h and r are closer to the standard one after compensating, meaning the measurement accuracy is much higher after using the compensation method. Therefore, the monitoring system is feasible for detecting roller wear.

If greater amplification is needed, both the distance between the roller axis and the detector (L) and the shift of the incident ray (S) can be increased. Also, an optical amplification system before CCD can be added to increase the amplification-ratio of this system.

6 Conclusion

A monitoring system for detecting roller wear measurement based on laser-linear CCD principle is proposed. The simulation-software of this system is also compiled to demonstrate the practicability of the measurement system for roller wear. After much study, the basic structure of this measurement system has been built. The advantages of the monitoring system for roller wear are structurally simply, highly amplified, non-contact, and applicable for on-line monitoring. In a low-cost situation, this system is a kind of effective measurement method.

The next step of this research is perfecting the simulation-software function, analyzing each kind of error and compensation algorithm. Also, the experiments taken at a work site are needed to make the system have more of an application value.

References

1. R. Kinose, "Development and application of build-in roll shaping machine for hot strip mill work rolls," *Iron Steel Eng.* **3**, 59–64 (1997).
2. J.-G. Cao, G.-C. Wei, and J. Zhang, "VCR and ASR technology for profile and flatness control in hot strip mills," *J. Cent. South Univ. Technol.* **15**(2), 264–270 (2008).
3. E. A. Garber, D. L. Shalaevskii, and I. A. Kozhevnikova, "Applicability of the laws of elasticity for the determination of the elastic-region length in the deformation zone during cold rolling," *Russ. Metall. (Metally).* **2008**(3), 205–209 (2008).
4. S. M. Byon, H. S. Park, and Y. Lee, "Experimental study for roll gap adjustment due to roll wear in single stand rolling and multi-stand rolling test," *J. Mech. Sci. Technol.* **22**, 937–945 (2008).
5. L. Nolle, "SASS applied to optimum work roll profile selection in the hot rolling of wide steel," *Knowledge-Based Systems.* **20**(2), 203–208 (2007).
6. G. Yuan and W. Yutian, "Study on an optical fiber on-line measurement system for roller wear," *Opto-Electron. Eng.* **193**, 82–85 (2005).
7. L. Zhao, H. Wang, and C. Xiao, "The influence of work roller diameter on shape of strip in stainless steel cold strip rolling process with numerical simulation method," *Adv. Mater. Res.* **538**, 646–650 (2012).
8. P. Kaixiang and Z. Donghua, "Data fusion based quality monitoring and control of strip thickness," *Adv. Mater. Res.* **230**, 266–273 (2011).
9. P. Jian et al., "Real-time displacement measurement immune from atmospheric parameters using optical frequency combs," *Opt. Express* **20**(24), 27133–27146 (2012).
10. G. Yuan, D. Xuefeng, and W. Yutian, "A novel optical fiber displacement sensor of wider measurement range based on neural network," *Proc. SPIE* **6150**, 61501O (2006).
11. G. Yuan, "A fiber-optic sensor for on-line non-touch monitoring roll shape," *Proc. SPIE* **7381**, 738111 (2009).

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