Fault Diagnosis of Roll Shape Under the Speed Variation in Hot Rolling Mill

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The metal processing system usually consists of various components such like motors, work rolls, backup rolls, idle rolls, sensors, etc. Even a simple fault in a single component in the system may cause a serious damage on the final product. It is therefore necessary to diagnose the faults of the components to detect and prevent system failure. Especially, the defects in a work roll are critical to the quality of strip. It is especially difficult to detect faults of a roll by using the existing frequency analysis method if the speed of the roll is changing. In this study, a new diagnosis method for roll eccentricity under the roll speed changes was developed. The new method was induced from analyzing the rolling mechanism by using rolling force models, radius -speed relationship, and measured rolling force, etc. Simulation results by using the field data show that the proposed method is very useful.

Key Words : Diagnosis, Eccentricity, Fast Fourier Transform (FFT), Rolling Force, Roll Shape Fault, Speed Variation

1. Introduction

The continuous processing systems such as multi-stand hot rolling systems generally consist of various components like driven rolls, idle rolls, sensors. In the rolling system, a work roll shape fault may cause a serious damage on the final products. Therefore, it is important to monitor the process systems and diagnose the component faults and draw up a scheme in order to minimize degradation of product quality and economic loss. For example, in steel rolling, the eccentricity of work roll has a fatal influence on strip thickness (Lee et al., 2004 ; Shin and Hong, 1998).

A 2-D diagnosis technique of the eccentricity of the roll by the using frequency analysis has been reported (Tahk and Shin, 2002). Eccentricity compensation methods have been proposed for tension control (Shin, 2003 ; 2000) and for roll gap control (Kugi et al., 2000). But most of the previous studies handled the fault diagnosis of roll shape in the region of steady state.

In this paper, a new diagnosis algorithm under continuous speed change is suggested to identify the defective work rolls on the basis of correlations among rolling force model, rolling mechanism, and system operating information. From the results of simulation, it is verified that the pro-

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posed diagnosis algorithm of roll shape detected the fault successfully even in the region of velocity variation of the roll.

2. Limitation of Frequency Analysis

Commonly, not in transient state but in steady state, Fast Fourier Transform (FFT) of the sampled rolling force signals is used to find a eccentricity of roll in rolling systems (Park et al., 2002). But a frequency of eccentricity can be changed according to the speed variation of the roll such as Fig. 1 in the real plant. Also, FFT result of a rolling force in the region of speed change has its magnitudes through all frequency domains such as Fig. 2. Thus it is hard to detect a eccentricity of a roll by using the FFT analysis in the region of speed change of a roll.

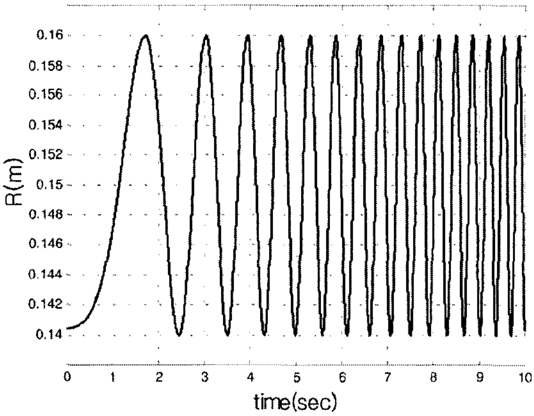

Fig. 1 Roll radius variation with angular velocity change

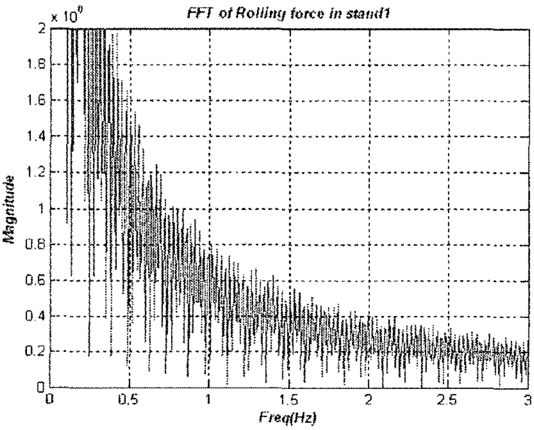

Fig. 2 FFT result of a rolling force

Thus it is necessary to develop an algorithm to detect roll defect under the speed variation of a roll.

3. Mathematical Models

Figure 3 shows a hot rolling process in which the strip thickness is reduced from h_{i-1} to h_i. The rolling force can be represented as the following Eq. (1) in hot rolling process (The Iron and Steel Institute of Japan, 1991). In Eq. (1), W is strip width, k_m is deformation constant, Q_p is rolling force constant, R' and is deformed roll radius. The k_m and Q_p is a function of temperature (Ginzberg and Ballas, 2000). Thus k_m and Q_p can be constant in the same temperature respectively. The mathematical model of forward slip (f_s) is such as Eq. (2). On the basis of correlation between work roll velocity (V_R), revolution per minute of roll (N), and outlet strip velocity (V), Eq. (3) is obtained. In Eq. (3), T_i, T_{i-1}, r means inlet tension, outlet tension, and thickness reduction rate respectively.

$$P = Wk_mQ_p\sqrt{R'(h_{i-1}-h_i)} \tag{1}$$

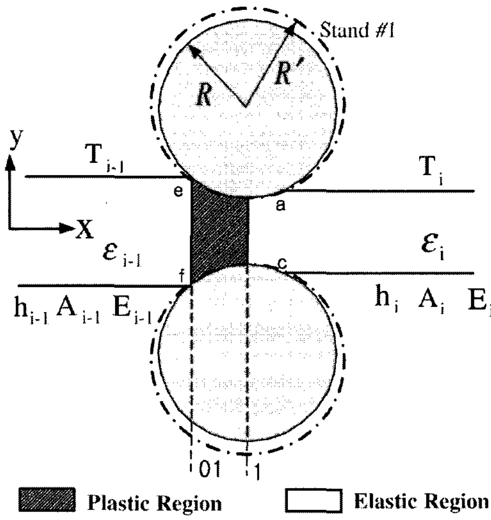

Fig. 3 A stand in hot rolling system

$$f_s=\tan^2\left\{\frac{1}{2}\tan^{-1}\sqrt{\frac{r}{1-r}}+\frac{\pi}{8}\sqrt{\frac{h_i}{R'}}\ln(1-r)+\frac{1}{2}\sqrt{\frac{h_i}{R'}}\frac{T_i-T_{i-1}}{k_m}\right\} \tag{2}$$

$$R'=\frac{60V_i}{2\pi N(1+f_s)} \tag{3}$$

Eq. (4) follows from Eqs. (1) and (3).

$$V=\frac{2\pi N(1+f_s)P^2}{60(h_{i-1}-h_i)(Wk_mQ_p)^2} \tag{4}$$

Outlet strip speed is tangential velocity at the 'a' point in Fig. 3 and tangential velocity is generally expressed such as Eq. (5).

$$V=R\omega \tag{5}$$

Finally Eq. (6) is derived from Eqs. (4) and (5). Eq. (6) shows relationship between rolling force and roll shape.

$$R(\theta)=\frac{2\pi N(1+f_s)P(\theta)^2}{60\omega(h_{i-1}-h_i)(Wk_mQ_p)^2} \tag{6}$$

In Eq. (6), since the work roll radius (R) and the rolling force (P) is function of the angle of the rotating roll, the change in the frequency of shape fault does not appear even with the speed variation of the roll. Therefore Eq. (6) can be applied for the diagnosis of roll shape under roll speed change.

4. Simulation Results

4.1 Simulations to verify the proposed model

A simulation study has been carried out to verify the performance of proposed diagnosis method. It is assumed that a roll has a fault such as periodic eccentricity in circumferential direction for the simulation.

Results of diagnosis for roll shape fault in the region of constant speed are as shown in Figs. 4 to 6. It is assumed that rolling force is measured such as Fig. 4. Through the radian based rolling force data and Eq. (6), the roll shape is estimated in the polar coordinate. Estimated roll shape seems to be perfect circle in Fig. 5, but small magnitude and location of eccentricity is amply confirmed in Fig. 6. In other words, not only magnitude

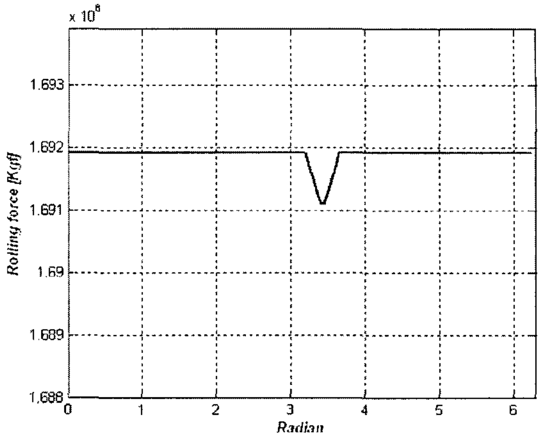

Fig. 4 Rolling force variation under constant speed

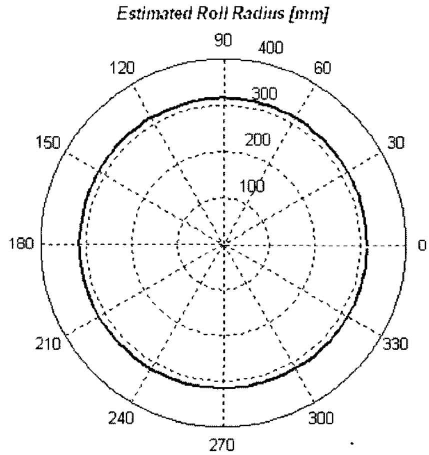

Fig. 5 Estimated roll shape in the polar coordinate

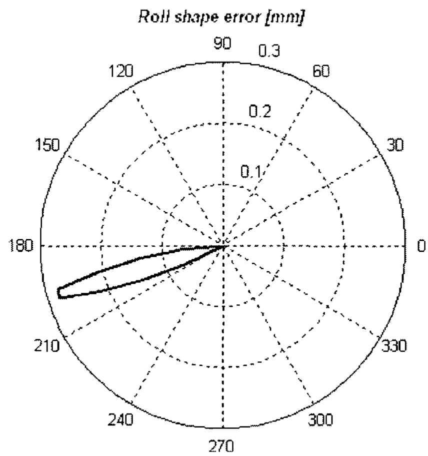

Fig. 6 Estimated eccentricity (magnitude, location)

of eccentricity but also location of eccentricity can be found through the proposed diagnosis method.

Table 1 Computer simulation parameters

Variables	values
Inlet thickness [mm]	10
Outlet thickness [mm]	6
Rolling temperature [K]	1178
Poisson's ratio	0.3
Scan time for rolling force measurement [sec]	0.05
Reference roll radius [mm]	187
Young's modulus [Kgf/mm²]	20408
Reference speed [mm/s]	1000~2300

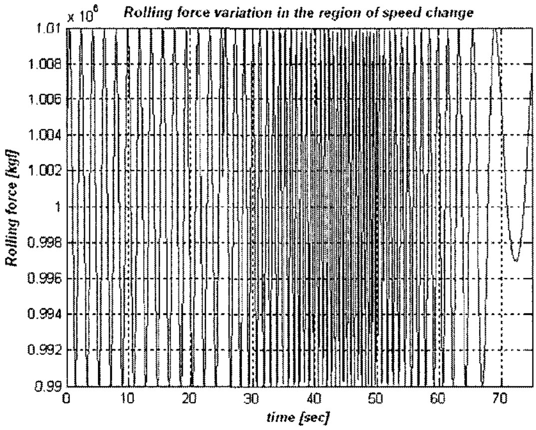

Fig. 7 Rolling force variation in the region of speed change of the strip

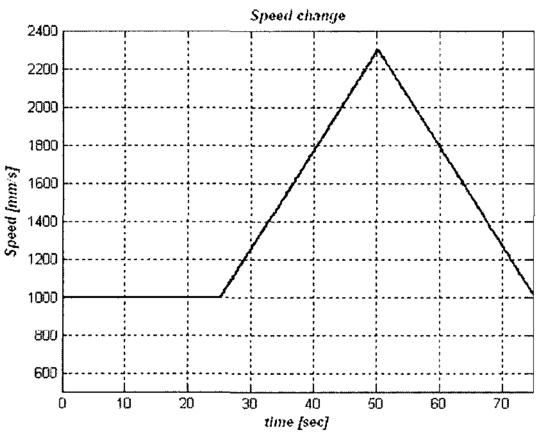

Fig. 8 Speed variation of roll

Table 1 shows the simulation data that are applied to roll shape fault diagnosis under roll speed variation. Rolling force variation in the region of speed change is as shown in Fig. 7. Fig. 8 shows speed variation of the roll from 1000 to 2300 mm/s. Through Eq. (7) that expresses the relationship between data scan time and angular velocity variation, the time based value $P(t)$ as shown in Fig. 7 can be transformed into the radian based value $P(\theta)$ as shown in Fig. 9.

$$\Delta\theta = scan\ time \times \Delta\omega \tag{7}$$

By using the measured rolling force and Eq. (6), the eccentricity can be diagnosed as shown in Figs. 11 and 12.

Figure 10 shows FFT result of the radian based value $P(\theta)$ as shown in Fig. 9. The magnitude at

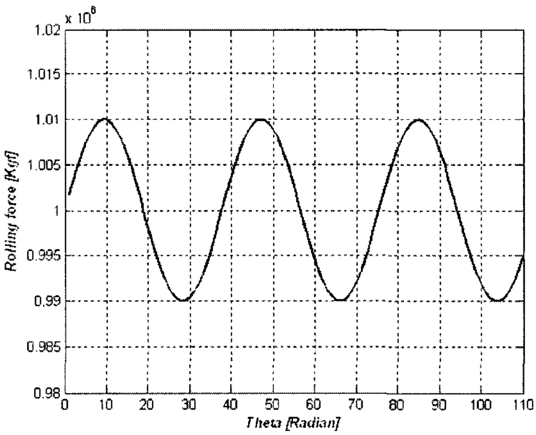

Fig. 9 Transformed rolling force

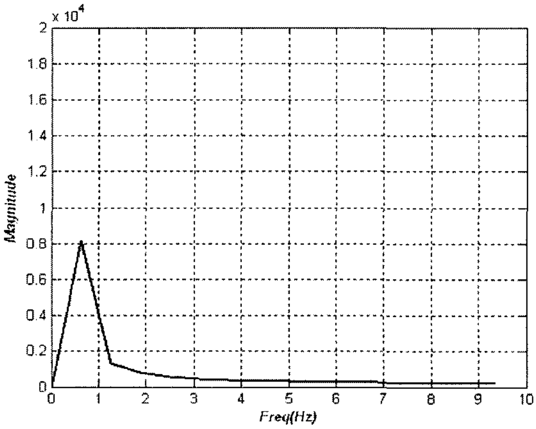

Fig. 10 FFT result of radian based value

the point of 0.6 Hz is relatively large as shown in Fig. 10. Therefore, from the FFT result as shown in Fig. 10, the only eccentricity existing can be detected. Fig. 11 shows the estimated roll shape by using the proposed diagnosis method as shown in Eq. (6). Not only the eccentricity magnitude but also fault location in cross-sectional area of roll is shown in Fig. 12. Roll shape error is obtained through Eq. (8).

$$Roll\ shape\ error = R_{reference} - R(\theta)_{Estimated} \quad (8)$$

By using the radian based value $P(\theta)$, frequency analysis method can be applied for the fault diagnosis in the region of speed change. But it is

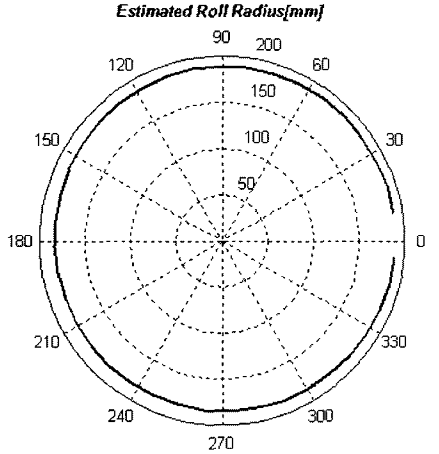

Fig. 11 Estimated roll shape in the polar coordinate

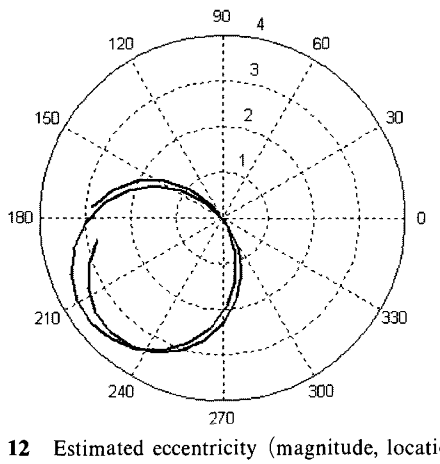

Fig. 12 Estimated eccentricity (magnitude, location)

impossible to find both eccentricity magnitude and eccentricity location in the roll as shown in Fig. 10. But, as shown in Fig. 12, not only magnitude of eccentricity but also location of eccentricity in the roll is obtained.

4.2 Simulations with field data

Figure 13 shows a simplified multi-stand hot rolling system. The rolling system consists of seven stands. Rolling force variation in each stand is as shown in Fig. 14. Especially, chattering of rolling force in the stand4 is bad in Fig. 14. This chattering of rolling force may be generated by work roll shape fault. Each velocity of rolls in the rolling system is accelerated or decelerated as shown in Fig. 15. Fig. 16 shows rolling force that is transformed into the radian based value by Equation (7). In Fig. 16, there is still serious chattering in stand4.

Table 2 shows simulation parameters used for diagnosis. In Fig. 17, the result of FFT for the transformed radian based rolling force shows only the eccentricity magnitude of roll in the stand4 without any information about eccentricity location in the eccentric roll.

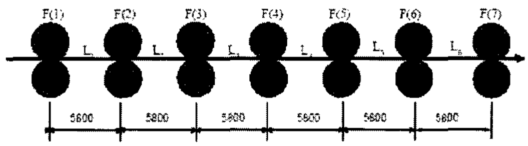

Fig. 13 Seven-stand hot rolling system

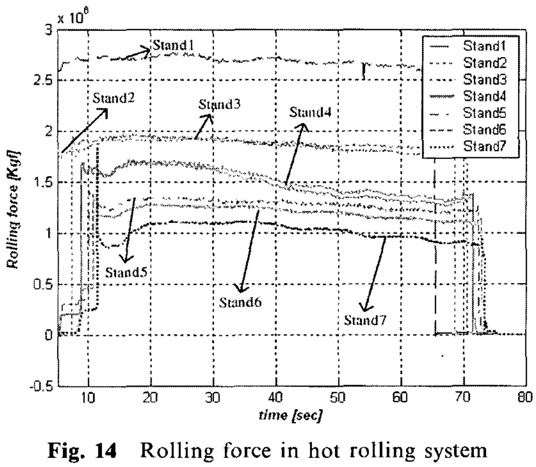

Fig. 14 Rolling force in hot rolling system

But, when the proposed diagnosis model as described by Eq. (6) with transformed rolling force data as shown in Fig. 16 was used, both eccentricity magnitude and eccentricity location in cross sectional area of the roll is detected as shown in from Figs. 18 to 20.

It is very difficult to measure the rolling temperature in real-time even though k_m and Q_b of Eq. (1) is sensitive to rolling temperature. What is more, the measured rolling force is not a function of angle (radian) but the function of constant scan time.

Therefore most of work rolls seem to have eccentricity as shown in From Figs. 18 to 20. Namely, small magnitude error of eccentricity may be generated because of rolling temperature error, noise, and sparse radian based rolling force data, and so on. Especially, magnitude error of eccentricity slightly large in Figs. 18 and 19 because rolling temperature variation is large in the fore part of seven-stand rolling system.

Although there are above difficulties for diagnosis of roll shape in hot rolling system, the roll shape fault can be identified through the proposed fault diagnosis method even with speed change of rolls. In Figs. 18 and 19, roll shape error does not exceed 0.1 mm. But Fig. 20 shows special shape error having the magnitude of 1 mm at 120 and 300 degree. This resulted from work roll shape fault in stand4. A magnitude and location of eccentricity can be detected through the proposed diagnosis method in the region of speed change.

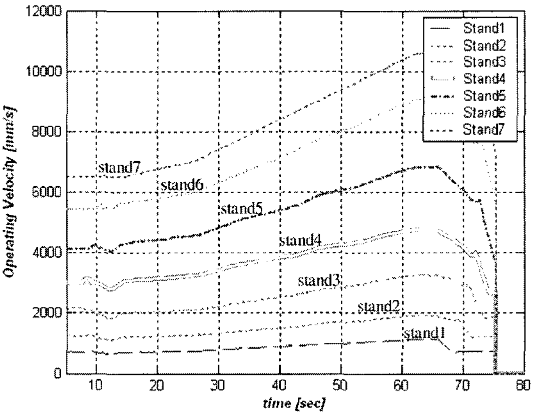

Fig. 15 Velocity of work roll in hot rolling system

Table 2 Field conditions

Variables	values
Initial thickness [mm]	29.6
Final thickness [mm]	1.59
Initial rolling temperature [K]	1229
Final rolling temperature [K]	1128
Poisson's ratio	0.3
Scan time for rolling force measurement [sec]	0.01
Amount of carbon [%]	0.048
Strip width [mm]	1240
Young's modulus [Kgf/mm^2]	20408
Strip speed [mm/s]	1000～11000

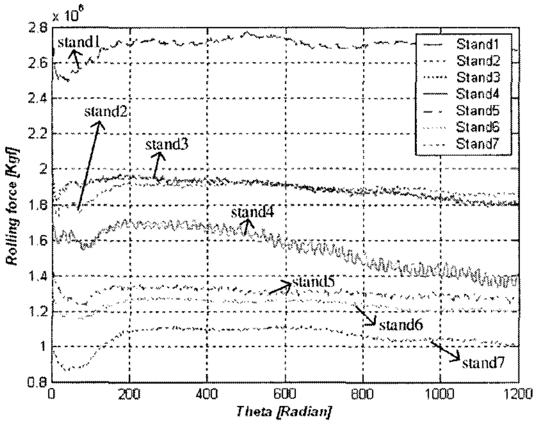

Fig. 16 Transformed rolling force

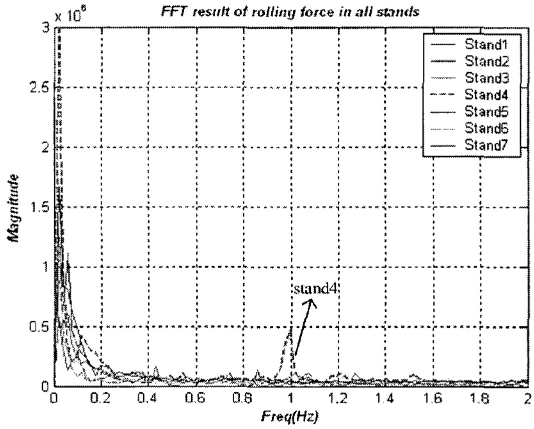

Fig. 17 FFT result of radian based value

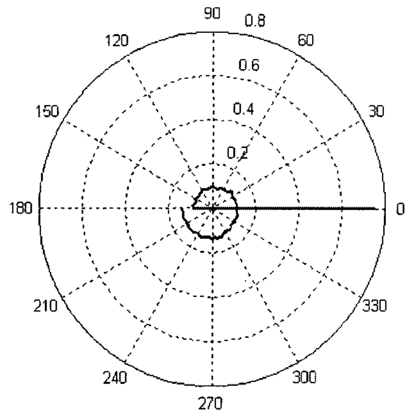

Fig. 18 Estimated eccentricity of work roll [mm] in stand1

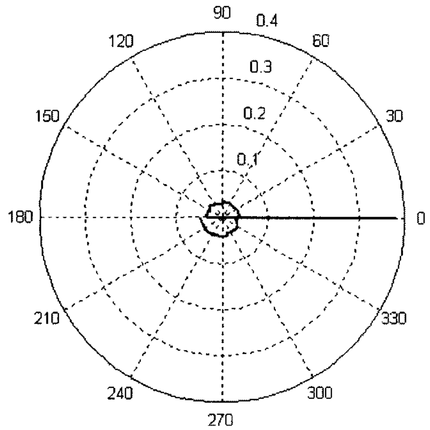

Fig. 19 Estimated eccentricity of work roll [mm] in stand2

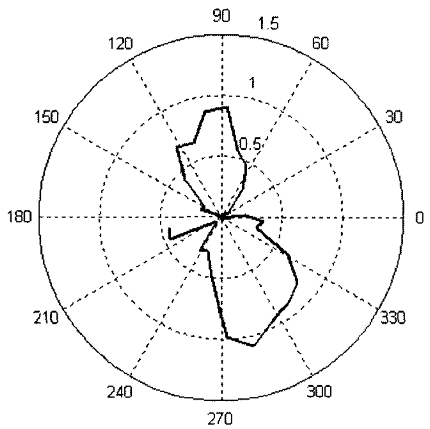

Fig. 20 Estimated eccentricity of work roll [mm] in stand4

5. Conclusions

This paper proposes a new diagnosis method of roll shape faults under the roll speed change. The mathematical models have been used to detect faulty roll in hot rolling systems. Both magnitude and location of eccentricity in the eccentric roll is obtained through the diagnosis method. Simulations and experiments were conducted to verify the performance of the proposed diagnosis method. The results show that the diagnosis method is greatly effective. The main results of the study are summarized as follows ;

(1) Mathematical model is developed for diagnosis of roll shape faults under velocity variation in hot rolling system.

(2) Faulty rolls are detected in the multi-stand rolling system without additional diagnosis instruments.

(3) Foundation for a roll shape fault tolerant control is prepared by detecting the magnitude and location of eccentricity.

(4) High frequency data of rolling force is needed to have a good diagnosis results when the proposed fault diagnosis method is used.

References

Bodson, M. and Douglas, S. C., 1997, "Adaptive Algorithm for the Rejection of Periodic Disturbances with Unknown Frequency," *Automatica*, Vol. 33, No. 12, pp. 2213~2221.

Ginzberg, V. B. and Ballas, R., 2000, *Flat Rolling Fundamentals*, Marcel Dekker, Inc., New York and Basel.

Kugi, A., Haas, W., Schlacher. and Aistleitner, K., 2000, "Active Compensation of Roll Eccentricity in Rolling Mills," *IEEE Transactions on Industry Applications*, Vol. 36, No. 2, March/April.

Lee, C. W., Kang, H. K. and Shin, K. H., 2004, "A Study on the Fault Diagnosis of the 3-D Roll Shape in Cold Rolling," *KSME International Journal*, Vol. 18, No. 12.

Park, C. J., Hong, S. C., Han, K. B. and Choi,

S. G., 2002, "Development of Thickness Diagnosis System in Hot Strip Mill," *Proceedings of the KAMES 2002 Joint Symposium A*, pp. 1028~1033.

Shin, K. H. and Hong, W. K., 1998, "Real-time Tension Control in a Multi-stand Rolling System," *KSME International Journal*, Vol. 12, No. 1, pp. 12~21.

Shin, K. H., 2000. *Tension Control*, TAPPI press, Technology Park/Atlanta.

Shin, K. H., Jang. J. I., Kang, H. K. and Song, S. H., 2003, "Compensation Method for Tension Disturbance due to an Unknown Roll Shape in a Web Transport System," *IEEE Transactions on Industry Applications*, Vol. 39, No. 5, September/October.

Tahk, K. M. and Shin, K. H., 2002. "A Study on the Fault Diagnosis of Roller-Shape Using Frequency Analysis of Tension Signals and Artificial Neural Networks Based Approach in a Web Transport System," *KSME International Journal*, Vol. 16, No. 12, pp. 1604~1612.

The Iron and Steel Institute of Japan, 1991, *Handbook of Steel Rolling ; Volume Three*, Sehwa Inc.