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J. S. Wang

University of Wollongong

Z. Y. Jiang

University of Wollongong, jiang@uow.edu.au

K. Tieu

University of Wollongong, ktieu@uow.edu.au

X. H. Liu

University of Wollongong, liuxh@uow.edu.au

G. D. Wang

University of Wollongong, guodong_wang@uow.edu.au

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A Method to Improve Model Calculation Accuracy of Process Control in Tandem Cold Mills

J. S. Wang^a, Z. Y. Jiang^a, A. K. Tieu^a, X. H. Liu^b, G. D. Wang^b

^a School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Wollongong NSW 2522, Australia

^b State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110004, P.R. China

Abstract—An adaptive learning algorithm using laser velocity meter is proposed for the process control of tandem cold mills. This method is used for on-line adaptive learning calculation of deformation resistance of strip and rolling friction models. The reverse calculation values of deformation resistance and friction coefficient as variables of non-linear equations can be obtained by introducing the measured rolling force and forward slip into the calculation model individually. Using Newton-Raphson iterative calculation to solve the non-linear equations, the reverse calculation values as actual values can be calculated. The actual forward slip obtained from the measured strip rolling speed using laser meter makes it possible that the deformation resistance of strip and friction coefficient can be uncoupled for model adaptive learning calculation. The inverse calculation and adaptive learning can improve whole control system of tandem cold mills significantly.

I. INTRODUCTION

The deformation resistance of rolled strip and friction coefficient are key factors for material properties and working feature of deformation zone for tandem cold rolling. The accuracy of the calculated deformation resistance and friction coefficient affects the rolling force model remarkably [1]. However, the calculation accuracy of model by itself cannot satisfy the requirement of on-line process control, so an adaptive learning method is adopted for practical control in plant. The measured parameters are essential for model adaptive learning calculation, but the deformation resistance and friction coefficient cannot be on-line measured directly until now. So, the backward calculation was carried out to introduce the measured values into the model and the unmeasured parameter could be calculated inversely, which was called inverse calculation value and used as a measured value for adaptive learning calculation. In general, the measured rolling force is used for the inverse calculation of deformation resistance or friction coefficient [2], but the two values cannot be obtained at the same time by this method, as the deformation resistance and friction coefficient are variables in rolling force model. A coupled relationship between the deformation resistance and friction coefficient in rolling force model can reduce the calculation accuracy of the two models and also of the rolling force model. With a practical application of laser velocity meter, the strip rolling speed can be measured accurately. In this paper, a new method is presented to improve the model calculation accuracy of rolling force using adaptive learning calculation.

II. CALCULATION MODELS OF PROCESS CONTROL

A. Rolling Force Model

The Bland-Ford-Hill model is used for rolling force calculation as shown in (1). The total rolling force includes the rolling forces in elastic and plastic deformation zones.

Total rolling force [3]:

$$F = F^p + F^e. \quad (1)$$

Rolling force in plastic deformation zone:

$$F^p = Q_f (k_m - \xi) b \sqrt{R' (h_{in} - h_{out})}, \quad (2)$$

where $\xi = \alpha \cdot \sigma_{in} + \beta \cdot \sigma_{out}$, $Q_f = 1.08 - 1.02 \cdot r + 1.79 \cdot r \cdot \mu \sqrt{1-r} \sqrt{\frac{R'}{h_{out}}}$

and the rolling force in elastic deformation zone:

$$F^e = F_{in}^e + F_{out}^e = \frac{2}{3} \sqrt{\frac{1-\nu^2}{E} k_m \frac{h_{out}}{h_{in} - h_{out}}} (k_m - \xi) \cdot b \sqrt{R' (h_{in} - h_{out})} \quad (3)$$

where F^p is the rolling force of plastic deformation zone, F_{in}^e the rolling force of elastic entry deformation zone, F_{out}^e the rolling force of elastic recovery deformation zone, b the strip width, σ_{in} the back tension, σ_{out} the front tension, μ the friction coefficient between the roll and strip, R' the flatten roll radius, Q_f the influence coefficient of friction, r the reduction at each pass, ν the Poisson ratio, E the Young's module, α the influence coefficient of back tension, β the influence coefficient of front tension.

B. Forward Slip Model

Fink model is adopted for the calculation of forward slip based on the velocity difference between the roll and strip. The neutral angle in the forward slip model is calculated by Bland-Ford equation. Forward slip model [2]:

$$f_s = \left(\frac{2R'}{h_{out}} \cos \Phi_n - 1 \right) (1 - \cos \Phi_n). \quad (4)$$

where Φ_n is the neutral angle, which can be written as [2]:

$$\Phi_n = \sqrt{\frac{h_{in}}{R'}} \tan \left[\frac{1}{2} \tan^{-1} \left\{ \sqrt{\frac{R'}{h_{out}}} \cos^{-1} \left(1 - \frac{1}{2} \frac{h_{in} - h_{out}}{R'} \right) \right\} - \frac{1}{4\mu \sqrt{\frac{R'}{h_{out}}}} \ln \left[\frac{h_{in}}{h_{out}} \frac{1 - \frac{t_{out}}{k_{in}}}{1 - \frac{t_{in}}{k_{out}}} \right] \right], \quad (5)$$

where f_s is the forward slip, h_{in} and h_{out} the strip thickness of entry and exit respectively, t_{in} and t_{out} the unit back and front tension respectively, k_{in} and k_{out} the strip deformation resistance of entry and exit respectively, μ the friction coefficient, Φ_n the neutral angle, R' the flatten roll radius.

C. Deformation Resistance Model

Considering the elastic deformation of the entry and exit of roll, the strip deformation resistance (6) is obtained according to the different deformation zones between the roll and strip [4]. Two adaptive learning coefficients C_{k0} and C_n are adopted for the modification of influence of material properties and reduction on deformation resistance. The adaptive learning includes additive term and exponential term modifications according to C_{k0} and C_n respectively.

$$k_m = \frac{2}{\sqrt{3}} C_{k0} k_0 \left(\frac{2}{\sqrt{3}} \ln \frac{100}{100 - \zeta \cdot r_m} + \varepsilon_0 \right)^{C_n \times n}, \quad (6)$$

where $r_m = \frac{h_0 - h_m}{h_0} \times 100$ and $h_m = (1 - \gamma) \cdot h_{in} + \gamma \cdot h_{out}$.

In the above models, k_m is the strip deformation resistance, h_0 the original strip thickness, h_m the thickness in deformation zone, γ the thickness influence coefficient, k_0 , ε_0 , n and ζ the model coefficients.

D. Friction Coefficient Model

The friction phenomenon is quite complicate during rolling and lots of factors influence the rolling friction [5, 6]. However, the on-line process control model cannot consider all these factors. The roll speed and rolled strip length, which are the most important factors for rolling friction, are considered and the statistical model of friction coefficient in this paper is shown in (7). The difference of friction coefficient between the actual and calculation values is compensated by the multiplicative term adaptive learning coefficient C_1 and exponential term coefficient C_2 in the model respectively.

Friction coefficient calculation model [4]:

$$\mu = \mu_L \cdot \mu_v + \mu_{min}, \quad (7)$$

$$\mu_L = C_1 \cdot a_L \cdot e^{b_L \cdot L + C_{L1} \cdot L^2 + d_L \cdot L^3 + e_L \cdot L^4}, \quad (8)$$

$$\mu_v = a_v \cdot \left\{ e^{C_2 [h_v (v-v_0) + c_v (v-v_0)^2 + d_v (v-v_0)^3 + e_v (v-v_0)^4]} \right\}, \quad (9)$$

where μ is the friction coefficient, L the rolled strip length, v the strip speed, μ_{min} the basic friction coefficient, $a_L - e_L$ and $a_v - f_v$ the model parameters, v_0 the basic strip speed, C_1 and C_2 the adaptive learning coefficients.

III. INVERSE CALCULATION METHOD

A. Tandem Cold Mill and Sensors.

The five stands tandem cold mill and layout of sensors are shown in Fig. 1. Six laser velocity meters and six tension meters are installed from the entry of No. 1 stand to No. 5 stand. Load cell is set for each stand for rolling load measurement. There are four gauge meters installed at the entry and exit of No. 1 and No. 5 stands for strip thickness measurement.

Fig. 1. Five stands tandem cold mill and sensors.

B. Algorithm

The measured rolling force is used in the rolling force model (1) and the high order equation, the inverse values k_{mi}^{back} and μ_i^{back} of deformation resistance and friction coefficient as variables, are shown in (10). The flatten radius R_i^{roll} is calculated by the flatten radius model using the measured values.

$$\begin{aligned} & \frac{2}{3} W \sqrt{R_i^{roll}} \Delta h_i^{meas} \sqrt{\frac{1-v^2}{E} \frac{h_i^{meas}}{\Delta h_i^{meas}}} \times \left(\sqrt{k_{mi}^{back}} \right)^3 + W \sqrt{R_i^{roll}} \cdot \Delta h_i^{meas} Q_{F1} \times k_{mi}^{meas} + \\ & \frac{2}{3} \{ -\alpha_i t_i^{meas} - \beta_i t_{i-1}^{meas} \} W \sqrt{R_i^{roll}} \cdot \Delta h_i^{meas} \sqrt{\frac{1-v^2}{E} \frac{h_i^{meas}}{\Delta h_i^{meas}}} \times \sqrt{k_{mi}^{back}} + \\ & \{ -\alpha_i t_i^{meas} - \beta_i t_{i-1}^{meas} \} W \sqrt{R_i^{roll}} \cdot \Delta h_i^{meas} Q_{F1} - F_i^{meas} = 0 \end{aligned} \quad (10)$$

The exit strip speed V^{meas} is measured by the laser velocity meter and the roll speed V_R^{meas} is obtained from code of motor.

The actual forward slip f_s^{meas} can be calculated according to the definition of forward slip between the roll and strip as shown in (11).

$$f_s^{meas} = \left(\frac{V_R^{meas}}{V_s^{meas}} - 1 \right) \times 100 \quad (11)$$

The actual value of forward slip is used in the forward slip model (4) and another high ordered equation (12), the inverse values k_{mi}^{back} and μ_i^{back} of deformation resistance and friction coefficient as variables, are deduced as follows:

$$\cos \left\{ \frac{1}{M_i} \tan \left[N_i - \frac{1}{4M_i \mu_i^{back}} \ln \left(\frac{h_{i-1}^{meas}}{h_i^{meas}} \times \frac{\eta_{kout} \cdot k_{mi}^{back} - t_{i-1}^{meas}}{\eta_{kmi} \cdot k_{mi}^{back} - t_{i-1}^{meas}} \right) \right] \right\} - \frac{(2M_i^2 + 1) - \sqrt{(2M_i^2 + 1)^2 - 8M_i^2 (f_{si}^{meas} + 1)}}{4M_i^2} = 0 \quad (12)$$

$$\text{where } M_i = \sqrt{\frac{R_{mi}^{mill}}{h_i^{meas}}} \text{ and } N_i = \frac{1}{2} \tan^{-1} \left[\sqrt{\frac{R_{mi}^{mill}}{h_i^{meas}}} \cos^{-1} \left(1 - \frac{1}{2} \frac{h_{i-1}^{meas}}{h_i^{meas}} \right) \right]$$

Simultaneous equations (13), the inverse values k_{mi}^{back} and μ_i^{back} of deformation resistance and friction coefficient as variables, are generated by (10) and (12). The variables in (13) are calculated at the same time by Newton-Raphson method.

$$\begin{cases} f_{si}^{meas}(\mu_i^{back}, k_{mi}^{back}) = 0 \\ F_i^{meas}(\mu_i^{back}, k_{mi}^{back}) = 0 \end{cases} \quad (13)$$

IV. ADAPTIVE LEARNING CALCULATIONS

A. Adaptive Learning of Deformation Resistance Model

The calculated deformation resistance values are as “actual values” and used for deformation resistance model (6) after inverse calculation. Equation (14) can be obtained after logarithmic transformation.

$$\ln(k_{mi}^{back}) = \ln \left(\frac{2}{\sqrt{3}} C_{k0} \cdot k_0 \right) + C_n \cdot n \cdot \ln \left(\frac{2}{\sqrt{3}} \ln \frac{100}{100 - \zeta \cdot r_{mi}} + e_0 \right) \quad (14)$$

Equation (14) can be set as a linear equation $Y_i = a_0 + a_1 \cdot X_i$, $X_i = \ln \left(\frac{2}{\sqrt{3}} \ln \frac{100}{100 - \zeta \cdot r_{mi}} + e_0 \right)$ is a known quantity and the unknown quantity is $Y_i = \ln(k_{mi}^{back})$ which includes the adaptive learning coefficients $a_1 = C_n \cdot n$ and $a_0 = \ln \left(\frac{2}{\sqrt{3}} C_{k0} k_0 \right)$.

Equation coefficients a_0 and a_1 can be calculated by linear regression method using the each stand actual (X_i, Y_i) - (X_s, Y_s) for 5 stands tandem cold mill. Furthermore, the adaptive learning coefficients $C_{k0} = \frac{\sqrt{3}e^{a_0}}{2k_0}$ and $C_n = \frac{a_1}{n}$ can be

obtained from a_0 and a_1 . The new adaptive learning coefficients are obtained by exponential smoothing calculation using the calculated coefficients of current rolled steel coil and preceding rolled steel coil as shown in (15) and (16).

$$C_{k0}^{next} = (1 - \alpha_{Ck0}) \cdot C_{k0}^{old} + \alpha_{Ck0} \cdot C_{k0}^{cal} \quad (15)$$

$$C_n^{next} = (1 - \alpha_{Cn}) \cdot C_n^{old} + \alpha_{Cn} \cdot C_n^{cal} \quad (16)$$

where C_{k0}^{next} , C_n^{next} the coefficients for next coil model setup calculation, C_{k0}^{old} , C_n^{old} the coefficients for preceding coil, C_{k0}^{cal} , C_n^{cal} the learning coefficients for current coil and α_{Ck0} , α_{Cn} the smoothing factors.

B. Adaptive Learning of Friction Coefficient Model

The calculated inverse value of friction coefficient is used in the friction coefficient model (7) and the adaptive learning coefficients C_1 and C_2 can be calculated. The update of learning coefficients of friction is same as the deformation resistance.

$$C_1 = \frac{\mu^{back} - \mu_{min}}{\mu_v (a_L \cdot e^{b_L \cdot L + e_L \cdot L^2 + d_L \cdot L^3 + e_L \cdot L^4})} \quad (17)$$

$$C_2 = \frac{\ln \left\{ \frac{\mu^{back} - \mu_{min}}{\mu_v} - f_v \right\} - \ln a_v}{\left\{ b_v (v^{back} - v_0) + c_v (v^{back} - v_0)^2 + d_v (v^{back} - v_0)^3 + e_v (v^{back} - v_0)^4 \right\}} \quad (18)$$

V. MODEL APPLICATION

The above models are used for on-line process control of 5 stands tandem cold mill. The technical parameters of the tandem cold mill are listed in Table 1. The rolling force statistic values of more than 150 rolling coil are shown in Figs. 2 and 3. The difference between the calculated and measured values with model adaptive learning is about $\pm 5\%$, however, it is $\pm 15\%$ without model adaptive learning. Therefore, the model with adaptive learning has improved the accuracy of process control significantly.

TABLE 1
EXPERIMENTAL PARAMETERS OF TANDEM COLD MILL

Parameters	Values
Work roll diameter [mm]	550
Work roll length [mm]	1220
Backup roll diameter [mm]	1320
Backup roll length [mm]	1092
Strip width [mm]	550 - 900
Strip thickness [mm]	1.5 - 3.5
Reduction [%]	20 - 40
Max motor power [kW]	3800

VI CONCLUSIONS

An algorithm is generated for the inverse calculation of deformation resistance of strip and friction coefficient in process control of tandem cold mill based on the application of laser velocity meters. Using the measured rolling force and forward slip, the inverse values of deformation resistance and friction coefficient, which are regarded as the “actual values” and used for adaptive learning of models, are obtained by solving the non-linear equations at the same time. The adaptive learning models are discussed for the learning coefficients calculations, which are used for the error compensation between the model calculation values and measured values. The practical application verifies that the inverse calculation and adaptive learning can improve the model accuracy significantly.

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Fig. 2. Comparison between calculated and measured rolling forces without adaptive learning.

Fig. 3. Comparison between calculated and measured rolling forces with adaptive learning.