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Coupled Dynamic Modeling of Rolls Model and Metal Model for Four High Mill Based on Strip Crown Control

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Abstract: The crown is a key quality index of strip and plate, the rolling mill system is a complex nonlinear system, the strip qualities are directly affected by the dynamic characteristics of the rolling mil. At present, the studies about the dynamic modeling of the rolling mill system mainly focus on the dynamic simulation for the strip thickness control system, the dynamic characteristics of the strip along the width direction and that of the rolls along axial direction are not considered. In order to study the dynamic changes of strip crown in the rolling process, the dynamic simulation model based on strip crown control is established. The work roll and backup roll are considered as elastic continuous bodies and the work roll and backup roll are joined by a Winkler elastic layer. The rolls are considered as double freely supported beams. The change rate of roll gap is taken into consideration in the metal deformation, based on the principle of dynamic conservation of material flow, the two dimensional dynamic model of metal is established. The model of metal deformation provides exciting force for the rolls dynamic model, and the rolls dynamic model and metal deformation model couple together. Then, based on the two models, the dynamic model of rolling mill system based on strip crown control is established. The Newmark-β method is used to solve the problem, and the dynamic changes of these parameters are obtained as follows: (1) The bending of work roll and backup roll changes with time; (2) The strip crown changes with time; (3) The distribution of rolling force changes with time. Take some cold tandem rolling mill as subject investigated, simulation results and the comparisons with experimental results show that the dynamic model built is rational and correct. The proposed research provides effective theory for optimization of device and technological parameters and development of new technology, plays an important role to improve the strip control precision and strip shape quality.

Key words: strip crown, transverse vibration of rolls, dynamic simulation, dynamic conservation of material flow

1 Introduction

With the development of economy, the strip plays more important role in the national economy. The high qualities of the strip are required, especially the crown and flatness. The rolling mill system is a complex, multivariable and nonlinear system. The crown and flatness qualities are influenced by many device parameters, technological parameters and controlling parameters. Dynamic model building of rolling mill can be used to model the practical experiment, can save the human power, material and financial resources. It is significant for optimizing the device parameters and technological parameters, implementing the technological policy and designing effective control system.

At present, the researches about the dynamic model building of rolling mill are mainly on the dynamic simulation of rolling mill system based on strip thickness control, and are rare on the dynamic simulation of rolling mill system based on the strip crown control, which reflect the dynamic characteristics of the strip along the width direction. For the studies on the dynamic simulation of rolling mill based on strip thickness control, Hessenberg and R.A. Phillips studied the tension and thickness of strip between stands in the tandem rolling under the condition that some stand was affected by external disturbances based on the theories of conservation of material flow, bounce equation of rolling mill, dynamic tension equation and thickness delay equation. KAMADA[1] studied the dynamic characteristics and new control method of tandem rolling process. ZHANG[2–3] studied the theory about the tension differential equation deeply in the tandem rolling. DUAN,

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et al[4], built the global coupled dynamic model of the typical complex electromechanical system. SUN [5] built the dynamic simulation model based on influence coefficient method, then the control model of rolling mill was built. PAN[6] developed the simulation software of cold tandem rolling. But the above researches about the dynamic characteristics of rolling mill were based on the strip thickness control system, and the dynamic characteristics of rolling mill based on the strip crown control and flatness control were not considered.

At present, the researches about the strip crown and flatness are mainly the static strip shape presetting theory and the research methods mainly include strip element method, finite element method, boundary element method and energy method[7–9]. There are few researches about the dynamic strip crown and flatness. WANG[10] studied the strip shape control problem of the strip threading process of tandem rolling process and forecasted the shape of thin sheet. SUN [5] designed the strip shape control system based on static crown presetting model. The above researches promoted the researches about dynamic strip crown and flatness, but they did not build the dynamic model of rolling mill based on strip crown and flatness control, and the dynamic simulation of strip crown was not given.

In this paper, the rolls were taken as elastic continuous bodies, the transverse dynamic model of rolls along the roll length direction was built; considering the dynamic characteristics of strip along the vertical direction, the two dimensional dynamic model of strip was built. Then, the transverse dynamic model of rolls and the strip dynamic model were coupled together. Finally, the dynamic model of rolling mill which can reflect the dynamic strip crown was built. Based on this nonlinear dynamic model, the suitable numerical method was selected, a custom rolling schedule of some tandem rolling mill was chosen as the simulation object, the dynamic characteristics of rolls and strip along the width direction were obtained.

2 Mathematic Model

2.1 Model structure and basic assumption

In the dynamic model of rolling mill based on strip crown control, the dynamic strip crown in rolling process is taken as simulation object. The dynamic model of rolling mill includes two sub-models which are the rolls transverse dynamic model and the strip dynamic model. The two sub-models coupled together, the rolls transverse dynamic model provides the displacement condition and velocity condition for the strip dynamic model, the strip dynamic model provides the exciting force for the rolls transverse dynamic model. The coupled dynamic model was built based on below assumptions.

(1) The rolling mill is a four high rolling mill;

(2) The rolling process is stable;

(3) The work roll and backup roll are connected by an elastic foundation;

(4) The rolls are simplified to freely support beam;

(5) The material of strip is homogenous;

(6) The deformation of strip obeys the two-dimension deformation theory.

2.2 Transverse dynamic model of rolls

Fig. 1 shows the physical model of rolls of four high mill. The distributed rolling force is imposed on the work roll, and the bending roll force is imposed on the work roll and the backup roll. In order to investigate the transverse dynamic characteristics of rolls, assuming that the rolls are homogenous, prismatic beams; the work roll and backup roll are connected by a Winkler elastic foundation, the elastic coefficient is K ; the work roll and backup roll are freely supported beams[11–13].

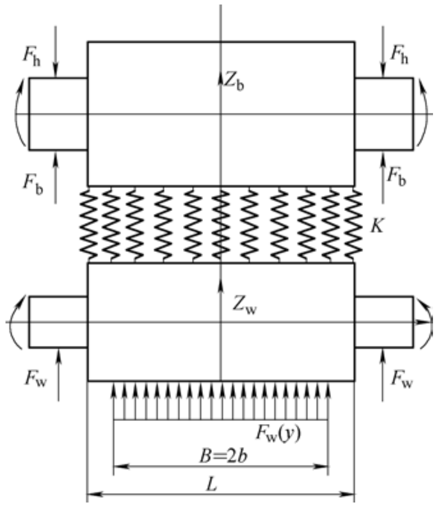

Fig. 1. Physical model of rolls for 4-high mill

Fig. 2 shows the mechanical model of the rolls. As can be seen, the work roll and backup roll are coupled by an elastic foundation. Their dynamic characteristics affect to each other. Assuming that the distributed rolling force and the bending roll force are imposed on the backup roll and the work roll for consistency. Actually, the backup roll does not subject to distributed rolling force.

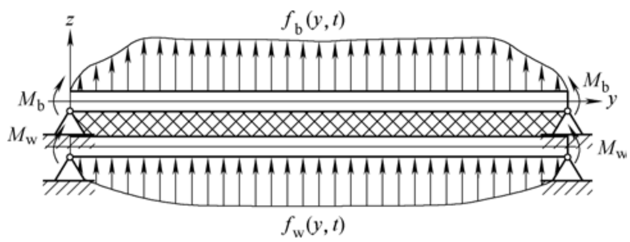

Fig. 2. Simplified mechanical model of rolls for 4-high mill

On the basis of Euler-Bernoulli model, assuming that the work roll and backup roll are of the same effective material constants, the governing differential equations of transverse vibration of rolls can be expressed by

$$E_b I_b z_b^{IV} + \rho_b A_b \ddot{z}_b + K(z_b - z_w) = 0, \tag{1}$$

$$E_{\rm w}I_{\rm w}z_{\rm w}^{\rm IV}+\rho_{\rm w}A_{\rm w}\ddot{z}_{\rm w}+K(z_{\rm w}-z_{\rm b})=f_{\rm w}(y,t), \tag{2}$$

where $z_i(y, t)$—Transverse deflection of rolls,
$f_i(y, t)$—Distributed rolling force,
E—Elastic modulus,
I—Moment of inertia of roll cross section,
ρ—Material density,
A—Area of cross section,
K—Elastic coefficient,
b, w—Backup roll and work roll.

Assume that $K_i=E_iI_i$, $m_i=\rho_iA_i$, $\dot{z}_i=\partial z_i/\partial t$, and $z_i'=\partial z_i/\partial y$ (i=b, w), then we have

$$K_{\rm b}z_{\rm b}^{\rm IV}+m_{\rm b}\ddot{z}_{\rm b}+K(z_{\rm b}-z_{\rm w})=0, \tag{3}$$

$$K_{\rm w}z_{\rm w}^{\rm IV}+m\ddot{z}_{\rm w}+K(z_{\rm w}-z_{\rm b})=f_{\rm w}(y,t). \tag{4}$$

The work roll and backup roll are assumed to be freely supported beams that are located on the elastic foundation. The boundary conditions and the initial conditions are respectively as follows:

$$z_i(0,t)=z_i''(0,t)=z_i(L,t)=z_i''(L,t)=0, \tag{5}$$

$$z_i(y,0)=z_{i0}(y),\ \dot{z}_i(y,0)=v_{i0}(y),\ \ i={\rm b,\ w}. \tag{6}$$

The differential Eqs. (3) and (4) represent the forced transverse vibration of rolls. In order to solve Eqs. (3) and (4), the natural frequencies and the corresponding mode shapes should be obtained by solving the free transverse vibration with appropriate boundary conditions firstly. For the free transverse vibration, Eqs. (3) and (4) become

$$E_{\rm b}I_{\rm b}z_{\rm b}^{\rm IV}+\rho_{\rm b}A_{\rm b}\ddot{z}_{\rm b}+K(z_{\rm b}-z_{\rm w})=0, \tag{7}$$

$$E_{\rm w}I_{\rm w}z_{\rm w}^{\rm IV}+\rho_{\rm w}A_{\rm w}\ddot{z}_{\rm w}+K(z_{\rm w}-z_{\rm b})=0. \tag{8}$$

With the governing boundary condition Eq. (5), Eqs. (7) and (8) can be solved by the Bernoulli-Fourier method. Assuming the solution in the form:

$$z_i(y,t)=\sum_{n=1}^{\infty}\sin(k_ny)T_{in}(t),\ \ i={\rm b,\ w}, \tag{9}$$

where $T_{in}(t)$ denotes the unknown time function, and $\sin(k_ny)$, $k_n=n\pi/L$ (n=1, 2, 3, $\cdots$), is the known mode shape function for simply supported roll.

Substituting Eq. (9) into Eqs. (7) and (8), and then solving the new equation yields the following frequency equation:

$$\omega_{1,2n}^2=0.5[(W_{{\rm b}n}^2+W_{{\rm w}n}^2)\mp\sqrt{(W_{{\rm b}n}^2-W_{{\rm w}n}^2)^2+4V_{\rm bw}^4}], \tag{10}$$

where ω_n denotes the natural frequency of rolls, and $W_{in}^2=(K_ik_n^4+K)m_i^{-1}$, $V_i^2=Km_i^{-1}$, $V_{\rm bw}^4=K^2(m_{\rm b}m_{\rm w})^{-1}$, i=b, w.

For each natural frequency, the associated amplitude ratios of vibration modes are given by

$$a_{in}=V_{\rm b}^{-2}(W_{{\rm b}n}^2-\omega_{in}^2)=V_{\rm w}^2(W_{{\rm w}n}^2-\omega_{in}^2)^{-1}. \tag{11}$$

Following the above analysis for the free transverse vibration of rolls, particular solutions of differential Eqs. (3) and (4) can be assumed to be the following form:

$$z_{\rm b}(y,t)=\sum_{n=1}^{\infty}\sin(k_ny)\sum_{i=1}^{2}S_{in}(t), \tag{12}$$

$$z_{\rm w}(y,t)=\sum_{n=1}^{\infty}\sin(k_ny)\sum_{i=1}^{2}a_{in}S_{in}(t), \tag{13}$$

where $S_{in}(t)$ (i=1, 2) denotes the unknown time function corresponding to natural frequency ω_{in}.

Substituting Eqs. (12), (13) into Eqs. (3), (4) yields

$$\sum_{n=1}^{\infty}X_n\sum_{i=1}^{2}(\ddot{S}_{in}+\omega_{in}^2S_{in})=0, \tag{14}$$

$$\sum_{n=1}^{\infty}X_n\sum_{i=1}^{2}(\ddot{S}_{in}+\omega_{in}^2S_{in})a_{in}=m_{\rm w}^{-1}f_{\rm w}. \tag{15}$$

Multiplying both sides of Eqs. (14) and (15) by eigenfunction X_m, integrating them from 0 to L with respect to y, and following the classical orthogonality condition, we have

$$\sum_{i=1}^{2}(\ddot{S}_{in}+\omega_{in}^2S_{in})=0, \tag{16}$$

$$\sum_{i=1}^{2}(\ddot{S}_{in}+\omega_{in}^2S_{in})a_{in}=2(Lm_{\rm w})^{-1}\int_0^L f_{\rm w}X_n{\rm d}y. \tag{17}$$

From Eqs. (16) and (17), the rolls transverse dynamic model can be obtained:

$$\ddot{S}_{in}+\omega_{in}^2S_{in}=H_{in}(t), \tag{18}$$

where

$$H_{1n}(t)=-2(a_{2n}-a_{1n})^{-1}\int_0^L(Lm_{\rm w})^{-1}f_{\rm w}\sin(k_ny){\rm d}y,$$

$$H_{2n}(t)=2(a_{2n}-a_{1n})^{-1}\int_0^L(Lm_{\rm w})^{-1}f_{\rm w}\sin(k_ny){\rm d}y.$$

2.3 Dynamic model of strip

In rolling process, the elastic-plastic deformation is produced in metal by the rolls. The traditional rolling theory thinks that, the metal deformation in rolling process obeys the principal of conservation of material flow, that is, the volume of metal flows into the roll gap is equal to the volume flows out of the roll gap, which is correct for the static analysis[14]. But the rolling process is dynamic, the rolls vibrate along the transverse direction and vertical direction. The dynamic characters of rolls and that of the metal influence each other. The metal not only moves along the pass line, but also moves along the vertical direction. So that, the dynamic characters of metal in rolling process were considered in this paper, the principal of dynamic conservation of material flow was put forward and the dynamic model of metal in rolling process was built.

Fig. 3 shows the geometry of roll gap in the rolling process. The work roll moves along z direction at the speed of $\dot{h}_c/2$, $\dot{h}_c$ is the roll gap change rate. So the metal in the roll gap also moves at the speed of $\dot{h}_c$, the deformation of metal is dynamic. Fig. 4 shows the rate of metal flow in the deformation zone. As can be seen, due to vertical vibration of the rolls, the metal also flows along vertical direction.

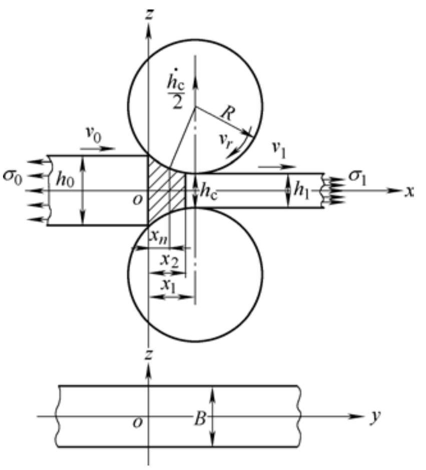

Fig. 3. Geometry of the roll gap in rolling process

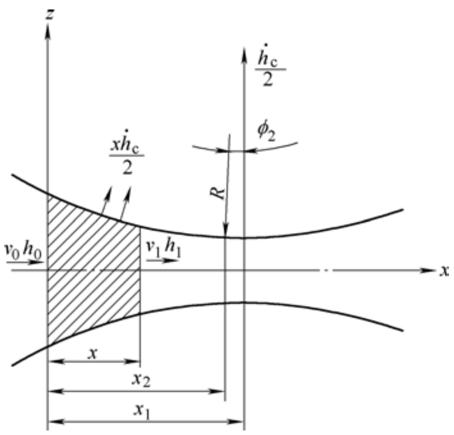

Fig. 4. Rate of metal flow in deformation zone

Applying the principle of dynamic conservation of material flow, the metal flow through a vertical cross-section at any arbitrary distance x can be written as

$$vh = v_0 h_0 - x\dot{h}_c, \tag{19}$$

where h —Thickness of strip at any arbitrary distance x,

v —Velocity at any arbitrary distance x,

h_0 —Thickness of entrance strip,

v_0 —Entrance velocity,

v_r —Circular velocity.

Using the parabolic approximation to the distribution for roll-bites, the distance from the cross-section of entrance of the strip to the center line of the work rolls can be written as

$$x_1 = \sqrt{R(h_0 - h_c)}, \tag{20}$$

where x_1 —Distance from the entrance of the roll-bite to the center-line of the work roll,

R —Radius of the work roll.

Considering the geometry in Fig. 3, one has

$$x_2 = x_1 - \frac{0.5Rh_c\dot{h}_c}{v_0 h_0 - x_1\dot{h}_c}, \tag{21}$$

$$h_2 = h_c + \frac{(x_1 - x_2)^2}{R}, \tag{22}$$

where x_2 —Strip exit position,

h_2 —Thickness of exit strip.

Fig. 5 shows a vertical slice of the metal sheet in the roll bite, the thickness is $\mathrm{d}x$, the tensile stress is σ_x, the friction is τ_s, the force equilibrium equation in x direction can be written as

$$\frac{\mathrm{d}h}{\mathrm{d}x}(p + \sigma_x) + h\frac{\mathrm{d}\sigma_x}{\mathrm{d}x} \pm 2\tau_s = 0, \tag{23}$$

where the minus is effective when $x < x_n$, the plus is effective when $x > x_n$. $\tau_s = \mu k\,(0 \leqslant \mu \leqslant 1)$, μ is friction factor.

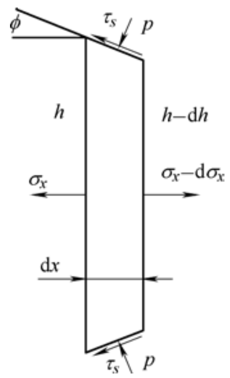

Fig. 5. Force diagram of metal element in deformation zone

According to Von Mises yield criterion in the plane strain, assume that σ_x and p are principal stresses, then the first order differential equation of the stress distribution can be written as

$$\frac{\mathrm{d}\sigma_x}{\mathrm{d}x} = \frac{2k}{h}\left[\pm\mu - \frac{2(x_1-x)}{R}\right]. \tag{24}$$

From Eq. (24), the exit stress can be obtained:

$$\sigma_1 = \sigma_0 + 2k\left\{\ln\frac{h_2}{h_0} + \mu\sqrt{\frac{R}{h_c}}\left[\arctan\left(\frac{x_1}{\sqrt{Rh_c}}\right) + \arctan\left(\frac{x_1-x_2}{\sqrt{Rh_c}}\right) - 2\arctan\left(\frac{x_1-x_n}{\sqrt{Rh_c}}\right)\right]\right\}. \tag{25}$$

From Eq. (25), the unit rolling force can be expressed as

$$p(x) = 2k - \left[\sigma_0 + \int_0^x \frac{2k}{h}\left(\pm\mu - \frac{2(x_1-x)}{R}\right)\mathrm{d}x\right]. \tag{26}$$

2.4 Coupled dynamic model of rolls and strip

According the rolls transverse dynamic model and strip dynamic model, coupled the two models, the coupled self-excited vibration model of rolling mill can be built, which can reflect the strip sectional form and the distributed rolling force. The first two order modes were considered in this paper, that is $n=1, 2$, combination of Eq. (18) and Eq. (26), one has

$$\boldsymbol{M}\ddot{x} + \boldsymbol{C}\dot{x} + \boldsymbol{K}x = \boldsymbol{F}, \tag{27}$$

where $x = (S_{11}\ S_{21}\ S_{12}\ S_{22})^{\mathrm{T}}$, $\boldsymbol{C} = 0$,

$$\boldsymbol{M} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \boldsymbol{K} = \begin{pmatrix} \omega_{11}^2 & 0 & 0 & 0 \\ 0 & \omega_{21}^2 & 0 & 0 \\ 0 & 0 & \omega_{12}^2 & 0 \\ 0 & 0 & 0 & \omega_{22}^2 \end{pmatrix},$$

$$\boldsymbol{F} = \begin{pmatrix} -2(a_{21}-a_{11})^{-1}\int_0^L (Lm_{\mathrm{w}})^{-1} f_{\mathrm{w}} \sin(k_1 y)\mathrm{d}y \\ 2(a_{21}-a_{11})^{-1}\int_0^L (Lm_{\mathrm{w}})^{-1} f_{\mathrm{w}} \sin(k_1 y)\mathrm{d}y \\ -2(a_{22}-a_{12})^{-1}\int_0^L (Lm_{\mathrm{w}})^{-1} f_{\mathrm{w}} \sin(k_2 y)\mathrm{d}y \\ 2(a_{22}-a_{12})^{-1}\int_0^L (Lm_{\mathrm{w}})^{-1} f_{\mathrm{w}} \sin(k_2 y)\mathrm{d}y \end{pmatrix}.$$

The distribution of exit thickness of strip reflects the shape of the roll gap, and the shape of roll gap is determined by the deformation of rolls and dynamic characteristic of rolls. One can see that, the rolls transverse vibration and the distributed rolling force are coupled together, the distributed rolling force influences the transverse roll gap, and the value of transverse roll gap influences the rolling force too, so that, the transverse roll gap and distributed rolling force need to be solved by iterative algorithm.

3 Solution of Coupled Dynamic Model

3.1 Solution procedure of coupled dynamic model

In the rolling process, due to the influences of external work environment and system parameters, the distributed rolling force will be changed, which lead to the vibration of rolls and change of transverse roll gap. Then, the change of the transverse roll gap will also lead to the change of the transverse distributed rolling force. The feedback self-excited vibration of rolling mill is formed by the transverse roll gap and the transverse distributed rolling force. Fig. 6 shows the flowchart of the calculation procedure.

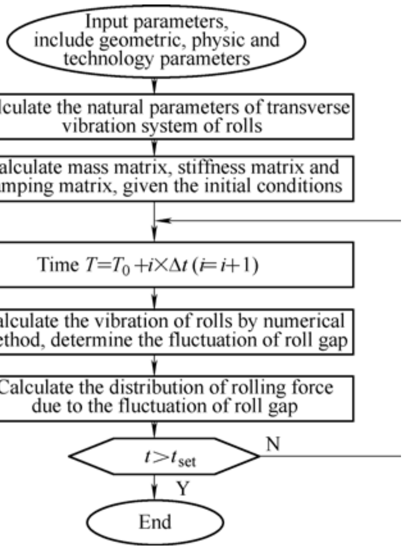

Fig. 6. Flow chart of the calculation procedure

3.2 Selection of the numerical method

From the above analysis, one can see that, the coupled dynamic model is a complex nonlinear dynamic model, which can not be solved directly, only to be solved by numerical method. At present, the numerical methods that used to solve complex nonlinear system include immediate integration method (Newmark-β method, Wilson-θ method), Runge-Kutta method and precise integration method. The immediate integration method requires that solve the implicit equation once in each integration step which needs the small integration step to guarantee the accuracy, and the calculation process is simple. The Runge-Kutta method is invalid for the singular problem and ill-conditioned matrix problem. The precise integration method need equivalence transformation for the ill-conditioned matrix problem, and its accuracy of calculation result is closed with the selection of additional stiffness[15].

Through equivalence transformation, Eq. (27) can be expressed as

$$\dot{\boldsymbol{X}} = \boldsymbol{H}\boldsymbol{X} + \boldsymbol{F}_n(\boldsymbol{X}, \dot{\boldsymbol{X}}, t), \tag{28}$$

where $\boldsymbol{H}$ is the equivalent matrix calculated by the known matrix $\boldsymbol{M}$, $\boldsymbol{K}$ and $\boldsymbol{C}$.

$$\boldsymbol{H}=\begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ \omega_{11}^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \omega_{21}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \omega_{12}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \omega_{22}^2 & 0 & 0 & 0 & 0 \end{pmatrix}.$$

According to the condition number of matrix $\boldsymbol{H}$, one can identify whether the matrix is ill-conditional matrix. Comprehensive analysis shows that, Newmark-β method is the most suitable method to solve the problem presented in this paper, its computation is simple and easy to implement, and choose a small integration step size can guarantee the accuracy.

4 Numerical Simulation

According to the above dynamic model, the dynamic simulation of rolling process was made. Take a rolling schedule of the second mill of some tandem rolling mill as subject investigated. Table 1 shows the main parameters used in the simulation.

Table 1. Simulation parameters

Parameter	Value
Diameter of work roll D_w/mm	615
Diameter of backup roll D_b/mm	1 550
Roll length L/mm	2 030
Strip width B/mm	1 006
Young's modulus E/GPa	210
Density ρ/(kg • m^{-3})	7.8×10^3
Elastic stiffness of foundation K/(GN • m^{-1})	60
Yield strength σ_s/MPa	337
Entrance thickness of strip H/mm	1.42
Exit thickness of strip h/mm	0.965
Forward stress σ_1/MPa	140
Backward stress σ_0/MPa	130

Based on the model assumptions, the simulation program can give the dynamic changes of the following parameters in the rolling process: (1) dynamic transverse changes of work roll and backup roll along the roll length direction; (2) variation of transverse distribution of roll gap with time, that is the dynamic changes of strip crown; (3) variation of distributed rolling force with time.

Fig. 7 shows the changes of distributed rolling force with time. One can see that, the rolling force is about 8 200 kN, it is very close to the measured value[14]. The simulation process is stable rolling process, and the bending roll force is assumed to be zero, the simulation result is approximate with the result calculated by finite element method[16]. All the above verify the correction of this model.

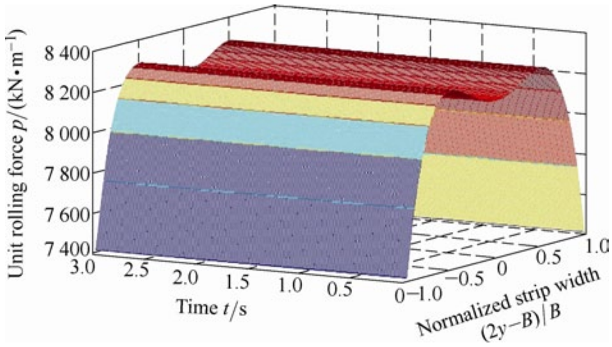

Fig. 7. Variation of distributed rolling force with time

Fig. 8 and Fig. 9 show the changes of work roll and backup roll with time under the distributed rolling force. One can see that, the curves of work roll and backup roll are quadratic curves and periodical change with time. The deflection of the work roll is about 40 μm, the deflection of the backup roll is about 7 μm. Because all the rolling conditions are ideal in the stable rolling process, so that the vibrations of work roll and backup roll are small, and are just simple periodical change.

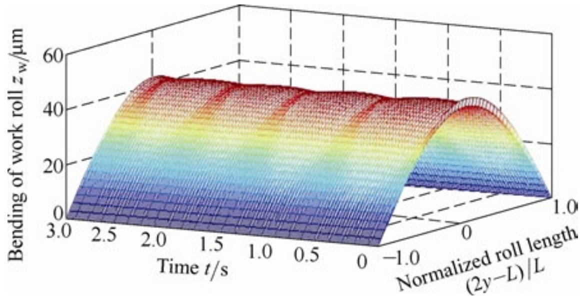

Fig. 8. Variation of bending deformation of work roll with time

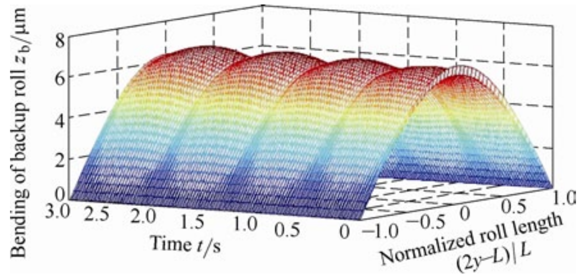

Fig. 9. Variation of bending deformation of backup roll with time

Fig. 10 shows the changes of distributed exit thickness of strip. The transverse distribution of roll gap is influenced directly by the vibration of the work roll and the backup roll, which can be reflected in the transverse distribution of exit thickness of strip. Assume that the shape of incoming strip is good, from Fig. 10 one can see that, the crown of exit strip is about 80 μm and periodical change with time. The simulation program can calculate the dynamic strip crown, but can not calculated the dynamic strip flatness (the dynamic distributed forward stress), which is the further research.

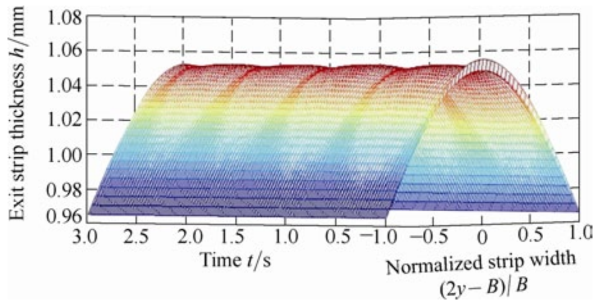

Fig. 10. Variation of distributed exit strip thickness with time

5 Conclusions

(1) The dynamic of four high rolling mill based on strip crown control was built, which included two coupled sub-models: transverse dynamic model of rolls and two dimensional dynamic model of strip.

(2) Solved the nonlinear dynamic model, selected the rational numerical method. Because the coefficient matrix of the nonlinear dynamic model is ill-conditioned matrix, so the Newmark-β method was selected as numerical method.

(3) The simulation program can calculate the dynamic changes of the following parameters in the rolling process: dynamic transverse changes of work roll and backup roll along the roll length direction; variation of transverse distribution of roll gap with time, which is the dynamic changes of strip crown; variation of distributed rolling force with time.

(4) Take some tandem rolling mill as subject investigated, the rolling force is very close to the measured value, the distribution of rolling force is agree with the actual situation; the bending of the work roll, the bending of the backup roll and the distribution of exit thickness calculated are real and rational. It is significant for optimizing the device parameters and technological parameters, implementing the technological policy and designing effective control system.

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