Analysis of Nonlinear Coupled Vibration Bifurcation Characteristic of Strip Mill under Dynamic Rolling Process

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Abstract: On the basis of dynamic rolling force, Duffing oscillator is taken as the nonlinear stiffness term between rolls of strip mill, considering the influence of periodic external excitation, and according to the symmetry of rolling mill structure, the nonlinear coupled vibration model of strip mill is established. The static bifurcation equation of coupled vibration system is obtained by using singularity, it is found that there are abundant static bifurcation behaviors in coupled systems. Finally, the dynamic bifurcation characteristics of coupled vibration system are obtained by numerical simulation, which can provide a theoretical reference for the control of coupled vibration of strip mill.

1. Introduction

Recently, there are some research results in the phenomenon and mechanism of coupled vibration [1][2][3]. The rolling friction and rolling force are coupled in reference[4], and the corresponding coupled vibration model is established, and the relation between friction factor and relative vibration velocity is given. Kapil and others studied the nonlinear characteristics of coupled vibration of four-high cold rolling mill under the parametric excitation[5]. Zeng and others established various coupling vibration relations and models by using dynamic rolling process model as a link, then the simulation results are compared with the vibration test data of 2030 cold rolling mill, which verify the validity and correctness of the model[6]. Through simulation and experiment in literature[7], it is verified that the vertical-horizontal coupling vibration model of rolling mill system is close to the actual situation. Peng and othersconsiders the external excitation and friction roll system of rolling mil, and the interaction of vertical-horizontal rolling force of roller system, finally the coupled flutter models of several cold rolling mills are established, and the influence of many nonlinear structural parameters and process parameters on coupled vibration of rolling mill is analyzed[8][9].

2. The Coupled Vibration Model of Strip Mill Under Dynamic Rolling Process

There are many vibration forms of strip mill, in the actual rolling process. The study has shown that the horizontal and vertical directions of roll system are coupled vibration, which influence each other. This paper introduces the concept of dynamic rolling force[10], which contains the dynamic changes of horizontal and vertical directions $\Delta p_x=a_1x+a_2y+a_3x^3+a_4y^3$ and $\Delta p_y=b_1x+b_2y+b_3x^3+b_4y^3$, among them, a_1~a_4 and b_1~b_4 are the undetermined parameter. Under the action of periodic external incentive $f\cos\omega t$, the vibration displacement of roll system of strip mill is x in horizontal direction , the vibration displacement is y in the vertical direction. And the Duffing oscillator $k_1+k_2y^2$ is considered as a nonlinear stiffness term, among them, k_1, k_2 are the stiffness coefficient. According to the symmetry of rolling mill structure, a nonlinear coupled vibration model of strip mill is established as shown in Fig. 1.

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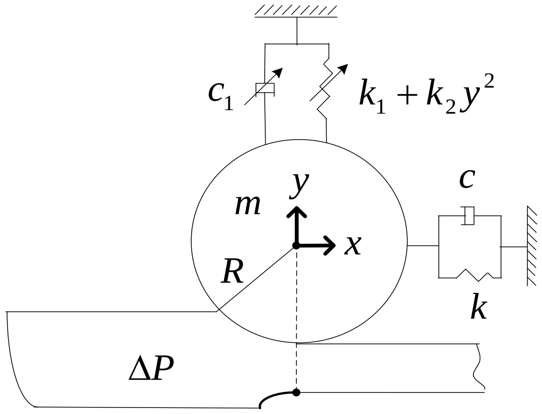

Fig.1 The coupled vibration model of strip mill in dynamic rolling process

$$\begin{cases} m\ddot{x} + c\dot{x} + kx + \Delta P_x = 0 \\ m\ddot{y} + c_1\dot{y} + (k_1 + k_2 y^2)y + \Delta P_y = f\cos\omega t \end{cases} \tag{1}$$

In (1): $\omega_1 = \sqrt{(k+a_1)/m}$, $\omega_2 = \sqrt{(k_1+b_2)/m}$, $\alpha_1 = c/m$, $\beta_1 = a_2/m$, $\gamma_1 = a_3/m$, $\varsigma_1 = a_4/m$, $\alpha_2 = c_1/m$, $\beta_2 = b_1/m$, $\gamma_2 = b_3/m$, $\varsigma_2 = (k_2+b_4)/m$, $F = f/m$. So the formula (1) can be written in the following form

$$\begin{cases} \ddot{x} + \omega_1^2 x + \alpha_1\dot{x} + \beta_1 x^2 + \gamma_1 x^3 + \varsigma_1 y^3 = 0 \\ \ddot{y} + \omega_2^2 y + \alpha_2\dot{y} + \beta_2 x + \gamma_2 x^3 + \varsigma_2 y^3 = F\cos\omega t \end{cases} \tag{2}$$

Formula (2) is the nonlinear coupled vibration dynamic equation of strip mill based on dynamic rolling process, which is the basis for further analysis of coupled vibration characteristics of rolling mills.

3. The Static Bifurcation Characteristics of Coupled Vibration System of Strip Mill

Solving formula (2) by using multiscale method, the amplitude-frequency response equation of nonlinear coupled vibration of strip mill can be obtained.

$$\begin{cases} \left((\sigma - \sigma_1)a + \dfrac{3}{8}\dfrac{\gamma_1}{\omega_1}a^2\right)^2 + \dfrac{\alpha_1^2}{4}a^2 = \dfrac{9}{64\omega_1^2}\varsigma_1^2 b^6 \\ \left(\omega_2\alpha_2 b^2 - \dfrac{\omega_1\alpha_1 a^2\left(4\beta_2 + 3\gamma_2 a^2\right)}{4\beta_1 + 3\varsigma_1 b^2}\right)^2 + (bF)^2 = \\ \left(\dfrac{4\beta_2 + 3\gamma_2 a^2}{3\varsigma_1 b^2}\left[2\omega_1 a^2(\sigma - \sigma_1) + \dfrac{3}{4}\gamma_1 a^4\right] + 2\omega_2\sigma b^2 + \dfrac{3}{4}\varsigma_2 b^4\right)^2 \end{cases} \tag{3}$$

σ and σ_1 are tuning parameters in formula, a and b are the amplitudes of coupled system of strip mill. Seen from Formula (3), the main parameters affecting the coupled vibration of strip mill are α, β, γ and ς , which are composed of the nonlinear coupling term of vibration displacement.

Static bifurcation characteristics of nonlinear coupled roll system of strip mill is study by using singularity theory. Order the amplitude $a^2=\mu_1$, $b^2=\mu_2$ in (3), and μ_2 is eliminated. The static bifurcation equation of coupled vibration system of strip mill is obtained as follows.

$$\mu_1^4 + \delta_3\mu_1^3 + \delta_2\mu_1^2 + \delta_1\mu_1 + \lambda = 0 \tag{4}$$

Formula (4) is a universal unfolding of the *GS* paradigm, the codimension is 3. Among them, δ_3 , δ_2 and δ_1 are the opening parameter, and λ is the bifurcation parameter. Finaly, this paper takes

δ_3=0 as an example, the static bifurcation characteristics of nonlinear coupled system of strip mill is studed.

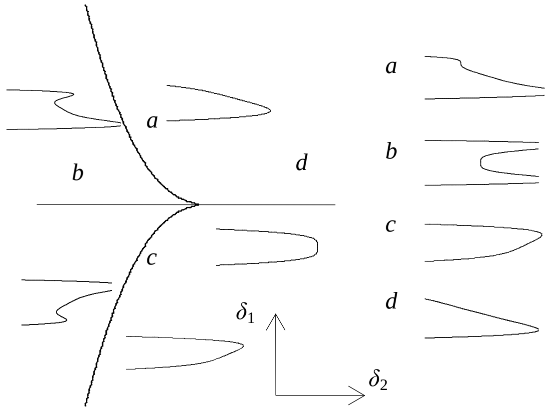

Fig. 2 The transition set and persistent bifurcation diagrams of coupling system

Fig. 2 shows the transition set of the coupled vibration system and the corresponding bifurcation curve, and the transition set divides the opening space of δ_1 -δ_2 into four subregions. In each subregion, the bifurcation form is similar, that is to say, the degradation is lasting. The bifurcation form is completely different in different regions, in other words, the degradation is unsustainable. Therefore, the opening parameters can be changed to control the dynamic behavior of the nonlinear coupling system of strip mill. thus the bifurcation characteristics of rolling mill system can be grasped as a whole and the theoretical prediction is made.

4. The Dynamic Bifurcation Characteristics of Coupled Vibration System of Strip Mill

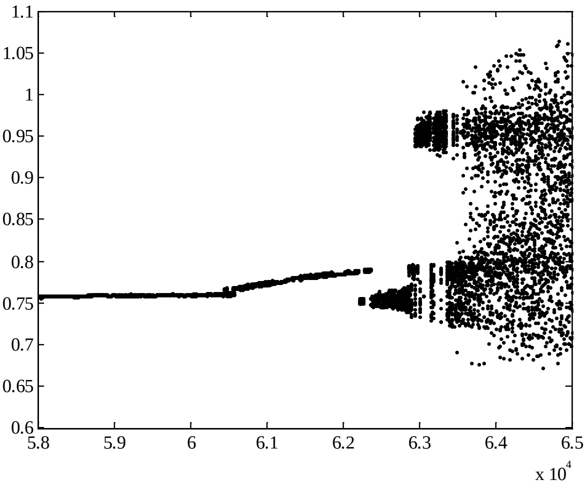

Fig.3 The dynamic bifurcation diagram of rolling mill nonlinear coupling system

Study the dynamic bifurcation diagram of the nonlinear coupled system of strip mill by using the numerical simulation. it can be seen from Fig.3, with the increase of external force, the nonlinear coupling system of strip mill moves from periodic motion to paroxysmal motion, and occurs jump bifurcation. With the F further increase, the irregular movement break out frequently in paroxysmal, which leads to chaotic motions.

5. Conclusion

Considering the factors such as nonlinear stiffness and structural parameters between roll system of strip mill, and introducing the concept of dynamic rolling force, finally the nonlinear coupled vibration model of strip mill is established. Amplitude-frequency response of the coupled vibration system is solved by multi-scale method, on this basis, the static bifurcation equation of the system is obtained by using the singularity theory. It is found that the dynamic behavior of nonlinear coupled system can be predicted and controlled by changing the opening parameters. Finally, the dynamic bifurcation and chaotic characteristics of the system are analyzed by using the numerical simulation.

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