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Torsional self-excited vibration of rolling mill①

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[Abstract] The roller's torsional self-excited vibration caused by roller stick-slip, and its influence on strip surface quality have been studied. Based on analysis of roller working surface stick-slip, roller rotation dynamics equations have been established. The nonlinear sliding-frictional resistance has been linearized, and dynamics equations have been solved according to the characteristics of stick and slip between roller and strip. The results show that: 1) with decreasing stick time t_1, torsional vibration wave pattern gradually transforms from serration into sinusoid, and frictional self-excited vibration can cover all frequency components which are lower than that of free vibration; 2) stick time t_1 is directly proportional to torque increment ΔM_R, and is inversely proportional to live shaft stiffness K and drive shaft rotational velocity ω; 3) when slip time t_2 is basically steady, the longer the stick time, the larger the energy that system absorbs and discharges. As the slip time is a constant, it easily arouses strip surface shear impact and surface streaks.

[Key words] rolling mill; drive; self-excited vibration
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1 INTRODUCTION

It is important problem that surface quality of rolling strip along with the automobile and building material industry development[1~5]. It often happens that the vibration of rolling mill arises, at the same time the strip surface appears stripe.

The events are often related to vibration, especially to self-excited vibration. Many peoples have investigated self-excited vibration[1~10], but the torsion self-excited vibration caused by sticking-sliding movement between rolling roller and strip was studied little. The dynamic friction force accused by relatively movement between roller and strip affects deformation of rolling strip. The variety friction force of working interface is mostly related with torsion vibration. The dynamic of rolling mill's working interface affects both stability of system and surface quality of strip. So it is important to investigate dynamic characteristics of a rolling mill drive system and the relationship between self-excited vibration and surface quality of rolling strip.

2 DYNAMIC MODEL OF RUNNING ROLLER

The roller of working rolling mill is run by transmission shaft, its torsion deformation is made by frictional force of rolling interface. There is relative movement between rolling roller and transmission shaft. Supposing the angle displacement is φ, the transmission shaft is running with invariableness rotate speed $\tilde{\omega}$, the dynamics equation of roller can be written as

$$J\ddot{\varphi} + c\dot{\varphi} + k(\varphi - \tilde{\omega}t) = M_R \quad (1)$$

where J is the inertia moment of roller, c is the damp, k is torsion stiffness, t is time, M_R is the friction moment,

$$M_R = F_R \cdot r_0$$

where F_R is the friction force.

Creep ratio between roller and strip is expressed as

$$\gamma_R = \frac{\dot{\varphi} \cdot r_0 - v}{v} \quad (2)$$

where v is the speed of strip, r_0 is the radius of roller.

The friction force of roller's working interface is complex, experiment and theory indicated that the relative movement between rolling roller and strip was sticking-sliding movement. The sticking interface of roller with strip becomes the least when wriggle slip ratio γ_R between roller and strip is greater than a certain value. At this time the friction force was peak value, then friction force suddenly dropped and made a leap.

In the sticking movement phase, the friction force F_R of sticking increases with the creep ratio γ_R and time t_1 and gradually reaches the peak value, as shown in Fig. 1. So we obtain

$$F_R = F_S - (F_S - F_D)e^{-\alpha_1} \quad (3)$$

where F_S is static friction force, F_D is dynamic friction force, α is determined by interface and material.

The friction force drops as increasing γ_R in sliding movement. Non-line sliding friction force is linearized in order to solve equation easily, as shown in

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Fig. 2. We obtain

$$F_R = F_D - b\dot{\varphi} \quad (4)$$

where b is the slope.

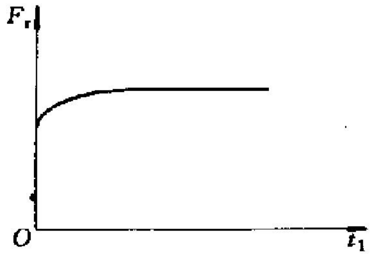

Fig. 1 Frictional force of sticking

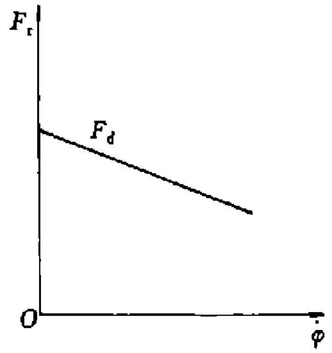

Fig. 2 Frictional force of sliding

As shown in Fig. 3, at the beginning of the roller sticking, the friction force value is F_D, the friction force gradually increases as the sticking motion time. Once the sticking of the roller is destroyed, the friction force value F_R drops back to F_D, which reduces linearly along with the relative slip motion increasing. On instant of sticking destroyed, the friction force makes a leap ΔF.

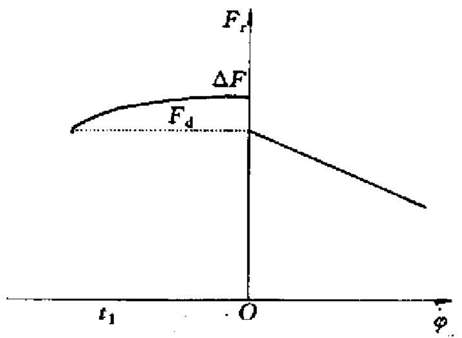

Fig. 3 Frictional forces of sticking-sliding

When the rolling roller is sticking on strip, the dynamic equation is written as

$$\dot{\varphi} = 0 \quad (5)$$

When the rolling roller is sliding on strip, the dynamic equation is written as

$$J\ddot{\varphi} + c\dot{\varphi} + k(\varphi - \tilde{\omega}t) = -(F_D - b\dot{\varphi})r_0 \quad (6)$$

3 ANALYSES OF DYNAMIC CHARACTERISTICS

The initial condition of the dynamic equations of rolling roller are expressed as

$$\ddot{\varphi}(0) = \Delta M_R/J = \Delta F \cdot r_0/J$$

$$\dot{\varphi}(0) = 0$$

Solve differential Eqn. (6), we obtain

$$\varphi(t) = e^{-\delta t}\Big[\Big(\frac{2J\delta\tilde{\omega}}{k} - \frac{M_D}{k}\Big)\cos\omega t + \Big(\frac{J\tilde{\omega}}{k}\frac{\delta^2 - \omega^2}{\omega} - \frac{\delta^2 - \omega^2}{2\delta\omega}\frac{M_D}{k} - \frac{\Delta M_R}{2\delta\omega}\Big)\sin\omega t\Big] + \tilde{\omega}t - \frac{M_D}{t} - \frac{(c-B)\tilde{\omega}}{k} \quad (7)$$

$$\dot{\varphi}(t) = e^{-\delta t}\Big[-\tilde{\omega}\cos\omega t + \Big(\frac{\Delta M_R}{J\omega} - \frac{\delta\tilde{\omega}}{\omega}\Big)\sin\omega t\Big] + \tilde{\omega} \quad (8)$$

$$\ddot{\varphi}(t) = e^{-\delta t}\Big[\frac{\Delta M_R}{J}\cos\omega t + \Big(\frac{k\tilde{\omega}}{J\omega} - \frac{\delta\Delta M_R}{J\omega}\Big)\sin\omega t\Big] \quad (9)$$

where $\delta = (c - B)/2J$, $\omega^2 + \delta^2 = k/J$, $B = b \cdot r_0$, ω is angular frequency of torsion.

From Eqns. (7) ~ (9) the motion of rolling roller is educed, as shown in Fig. 4. ϕ is relatively angle displacement of rolling roller, $\phi = \tilde{\omega}t - \varphi$. $\tilde{\omega}$ is the speed of transmission shaft, φ is angle displacement of rolling roller; t_0 is the total time, t_1 is time of sticking, t_2 is time of sliding. The system of rolling mill absorbs energy when rolling roller is screwing, and releases energy when rolling roller is slacking. Because $t_2 < t_1$, the system of rolling mill takes longer time to absorb energy than to release energy.

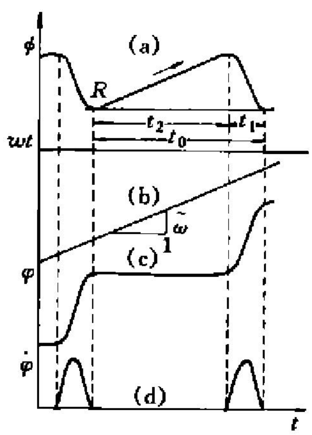

Fig. 4 Running motion chatter of roller

From Eqn. (6) and Fig. 4, we can find

$$\dot{\varphi}(t_2) = \ddot{\varphi}(t_2) = 0 \quad (10)$$

Substituting Eqns. (7) and (8) into Eqn. (9), then we have

$$\begin{vmatrix} e^{\delta t_2} - \cos wt_2 - \frac{\delta}{\omega}\sin\omega t_2 & \frac{1}{J\omega}\sin\omega t_2 \\ \frac{k}{J\omega}\sin\omega t_2 & \frac{1}{J\omega}(\cos\omega t_2 - \delta\sin\omega t_2) \end{vmatrix} = 0 \quad (11)$$

The sliding time t_2 can be determined by

$$\cos\omega t_2 - \frac{\delta}{\omega}\sin\omega t_2 = e^{-\delta t_2} \quad (12)$$

Eqns. (7), (8) and (9) indicate that φ, $\dot{\varphi}$ and $\ddot{\varphi}$ charge with angle frequency ω in sliding motion. When $\omega < \sqrt{k/J} = \omega_n$, i, e. ω is less than the natural frequency ω_n, commonly $\delta^2 \ll \omega^2$, so that $\omega = \omega_n$.

From Eqn. (12), we have

$$\Delta M_R/\tilde{\omega} = -\frac{k}{\omega}e^{-\delta t_2}\sin\omega t_2 \quad (13)$$

As δ is very little, the motion of running rolling roller is periodic. We have

$$(t_1 + t_2)\tilde{\omega} = \varphi(t_1) = \varphi(t_2) \quad (14)$$

From Eqns. (12) and (13), the sticking time can be determined as

$$t_1 = -\frac{1}{\omega}e^{\delta t_2}\sin\omega t_2 = \Delta M_R/\tilde{\omega}k \quad (15)$$

Obviously, sticking time is in the direct ratio with tweak increment ΔM_R and in the inverse ratio with torsion stiffness k and speed of axis of rotation $\tilde{\omega}$. From $\omega = \omega_n$, we can think that t_2 is stabilization. Fig. 5 shows that torsion vibration Φ from hackle wave turns into sine wave along with sticking time reducing (a) → (b) → (c). As shown in Fig. 5(c), the frequency of friction self-excited vibration is approximately equal to frequency of natural vibration.

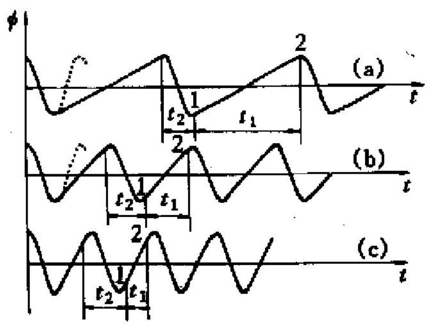

Fig. 5 Relative motion between roller and strip

4 INDUSTRIAL SCENE TEST

The dynamic characteristics of a great steel company's temper mill(CMO4) had been calculated and tested, natural frequency of main driving system was calculated, as shown in Table 1[6].

The vibration of main driving system in the temper rolling mill had been tested. Tested frequency chart shows that the frequency of vibration perk value (12.5 Hz) is approximately equal to frequency of natural vibration (12.458 Hz). This indicates that the vibration of main driving system in the temper rolling is self-excited vibration. Its vibration frequencies are firstly order natural frequency of main driving system.

Table 1 Natural frequency

Order	One	Two	Three
Natural frequency/Hz	12.46	54.03	164.08

From foregoing analysis, the sticking time t_1 is changing as the tweak increment ΔM_R, torsion stiffness k and speed of axis of rotation charge $\tilde{\omega}$. We are able to educe that sticking t_2 is nearly invariable due to $\omega = \omega_n$. The greater tweak increment ΔM_R is, the more the system of rolling mill absorbs and stores energy from environment. Because sliding time is short and releasing energy is great when the rolling roller is sliding, they easily cause cutting impacts and stripes on strip surface.

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