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Characteristic of Torsional Vibration of Mill Main Drive Excited by Electromechanical Coupling

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Abstract: In the study of electromechanical coupling vibration of mill main drive system, the influence of electrical system on the mechanical transmission is considered generally, however the research for the mechanism of electromechanical interaction is lacked. In order to research the electromechanical coupling resonance of main drive system on the F3 mill in a plant, the cycloconverter and synchronous motor are modeled and simulated by the MTLAB/SIMULINK firstly, simulation result show that the current harmonic of the cycloconverter can lead to the pulsating torque of motor output. Then the natural characteristics of the mechanical drive system are calculated by ANSYS, the result show that the modal frequency contains the component which is close to the coupling vibration frequency of 42Hz. According to the simulation result of the mechanical and electrical system, the closed loop feedback model including the two systems are built, and the mechanism analysis of electromechanical coupling presents that there is the interaction between the current harmonic of electrical system and the speed of the mechanical drive system. At last, by building and computing the equivalent nonlinear dynamics model of the mechanical drive system, the dynamic characteristics of system changing with the stiffness, damping coefficient and the electromagnetic torque are obtained. Such electromechanical interaction process is suggested to consider in research of mill vibration, which can induce strong coupling vibration behavior in the rolling mill drive system.

Keywords: rolling mill vibration, current harmonic, speed oscillation, electromechanical coupling, vibration characteristic

1 Introduction

The vibration of the rolling mill is a difficult problem, and affects the quality of the strip production. Many scholars have carried out a lot of research on the mechanism of rolling mill vibration[1]. The main factors of consideration include the load of rolling[2–3], mechanical drive sturce[4], screw down system[5] and roll gap lubrication[6], et al.

In recent years, with the improvement of equipment level of complex electromechanical system, more and more coupling vibration problems occur in the working process. It has been involved with maglev trains[7], hybrid cars[8], computer numerical control(CNC) machines[9] and large generators team[10]. Research show that in these complex electromechanical system, there are many kinds of coupling behavior[11], such as directly electromagnetic torque coupling, electromagnetic parameter coupling vibration and variable control parameters coupling, and so on. According to the research of the coupling vibration of rolling mill, there are also many kinds of coupling vibration behavior in the rolling mill system[12].

The main study of the coupling vibration generally consists of three cases. One is coupling of vertical vibration and the dynamic rolling process of rolling mill, which not only influence the stability of this rolling mill, but also affect the adjacent mill through the interstand[13–14]. Another is coupling of vertical and horizontal vibration, this research is carried out by establishing the coupling model of the mechanical structure system of the mill[15]. There is also the electromechanical coupling vibration in the rolling mill. The typical vibration mode is the torsional vibration of main drive system, and the research object is the rolling mill's electric system and the mechanical system[16]. When the regulating frequency of control system is close to the natural frequency of mechanical system, the electromechanical resonance happen[17]. In flexible thin slab casting and rolling(FTSR) mill system, the abnormal vibration is caused by coupling vibration of control system oscillation and horizontal vibration of roll system in main drive system, when the frequency of the torsional vibration is equal to the horizontal natural frequency of the roll system, the horizontal vibration takes place most severely[18]. In compact strip production(CSP) mill system[19], self-made comprehensive telemetry system is used to test the rolling mills vibration parameters, force and energy parameters,

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electric parameters and technological parameters on site. Analysing the test signal in the time and frequency domain, characteristics and rules of vibration can be obtained. Through the theoretical and simulation research, it is found that rolling mill do exist vertical-twist coupling vibration, electromechanical coupling vibration and liquid-mechanical coupling vibration phenomenon. In addition, nonlinear theory is used for the research of the electromechanical coupling of rolling mill[20]. So much research has greatly enriched the contents of coupling vibration of mill drive system. But most of the research focus on the dynamic performance of the system which is effected by a kind of coupling behavior. In fact, during the process of electromechanical energy conversion, the correlation of all kinds of coupling behavior exist, for this case, the system will show a more complex dynamic characteristic.

In this paper, by building a simulation model of variable frequency synchronous motor of the main drive, the interaction of harmonic current and mechanical speed is explored. Based on the testing signal on site and the nonlinear dynamic characteristics of mechanical drive structure, the coupling behavior and characteristic are researched.

2 Problem

The F3 mill often vibrate when rolling thin strip steel in a factory. Using torque telemetry system to test the torsional vibration on the motor output shaft of main drive system, signals show that, as the rolling speed changes, the main frequency of vibration changes accordingly, and at a defined speed, vibration intensity change also, the system shows nonlinear dynamics characteristic. Typical torsional vibration waveform and spectrum is shown in Fig. 1(a) and Fig. 1(b).

Furthermore, test shows that there are relevant frequency components existing in the current waveform of motor torque current(Fig. 1(c)), preliminary judgment is that the torsional vibration in the main drive system is caused by the electromechanical coupling resonance. In order to explain the vibration mechanism, it should be researched from both electrical and mechanical system.

3 Generation of Electric System Harmonic

3.1 Generation of current harmonic

Electrical system contains many nonlinear elements, such as converter switch. Power of the rolling mill is supplied by the cycloconverter. Using the Matlab/Simulink SimPowerSystems modules, a three phase alternating current(AC) model is established in Fig. 2.

According to the rolling speed, the converter output frequency is selected for 7 Hz. After simulation, the output current waveform is shown in Fig. 3.

Fig. 3 shows that, in addition to the fundamental wave, the converter output current contains many harmonic components. It can be inferred that the current harmonic component in cycloconverter output make effect on the motor output torque.

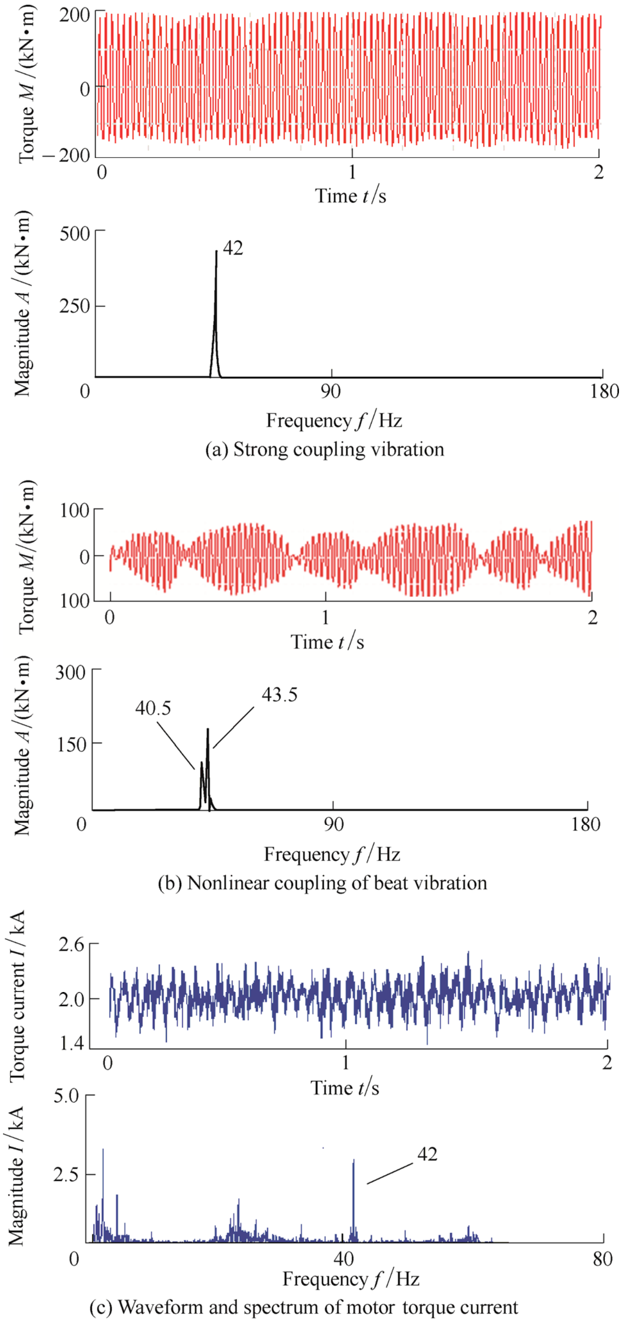


Fig. 1. Phenomenon of electromechanical coupling vibration

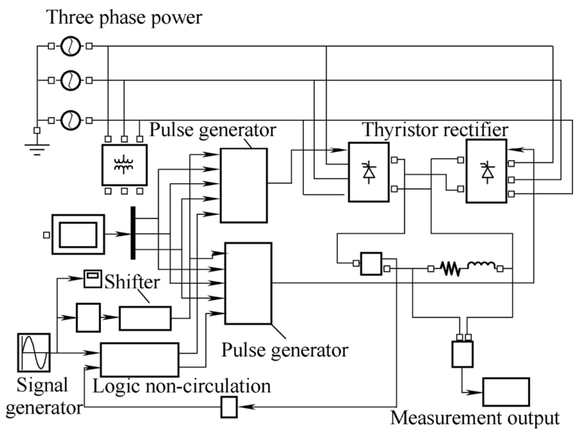


Fig. 2. Single phase cycloconverter model

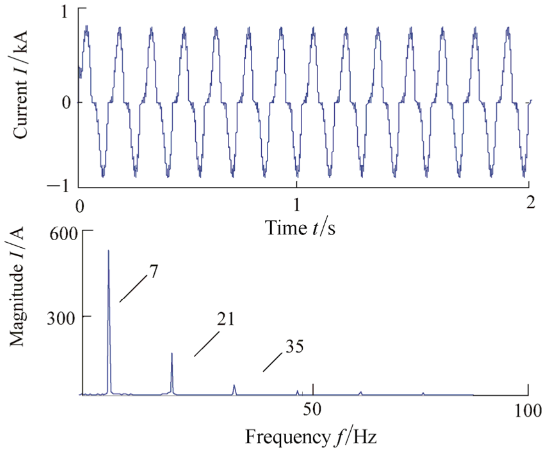


Fig. 3 Cycloconverter output current spectrum

3.2 Generation of torque harmonic

In order to research the process that the cycloconverter output current with harmonic component change to the output torque of the motor through the coupling of magnetic field of synchronous motor, the whole model of cycloconverter and synchronous motor is set up and shown in Fig. 4.

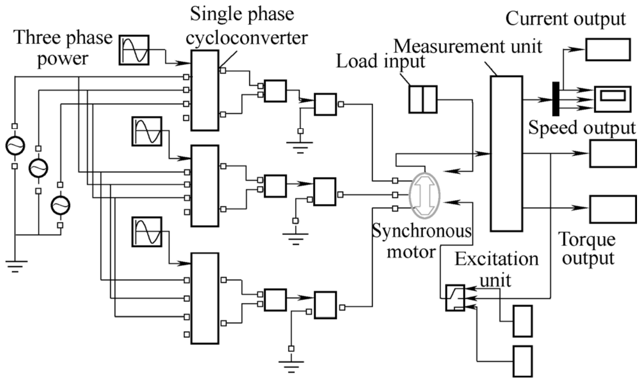


Fig. 4. Model of three-phase cycloconverter and motor

In Fig. 4, each group of cycloconverter supplies power to each phase of synchronous motor, respectively. The motor is assumed operating in nominal conditions, and the numerical values of parameters are given in Table 1.

After simulation, the output of the motor stator current and electromagnetic torque waveform are shown in Fig. 5 and Fig. 6.

Fig. 5 shows that stator current contain 35 Hz(5th) and 49 Hz(7th) harmonic component in addition to the fundamental frequency 7 Hz when motor is supplied by cycloconverter. Electromagnetic torque signal contains 42 Hz frequency component. It can be inferred that the harmonic of stator current is the main reason which cause the motor output shaft vibration[21–22].

Actually, when the harmonic current flows into the three-phase stator coil winding, alternating magnetic potential is induced in the winding, then the alternating magnetic potential can produce harmonic magnetic potential with the same frequency in the magnetic field of motor. In static three-phase coordinate axis, the 5th harmonic current vector and fundamental wave current vector rotate in opposite directions, 7th harmonic current vector and fundamental wave current vector rotate in same directions[23–24], assuming that three phase current(i_a, i_b, i_c) can expressed as follows:

Table 1. Parameters of synchronous motor

Parameter	Value
Rated voltage/V	924
Rated current/A	3 695
Rated power/kW	10 000
Rated speed/(r • min^{-1})	140/440
Rated frequency/ Hz	7/22
Motor inertia/(kg • m^2)	8 600
Number of pairs of poles	3
Exciting current/ A	325
Stator resistance/ p.u	0.018
Stator leakage inductance/ p.u	0.091
D-axismagnetizing inductances/ p.u	1.628
Q-axis magnetizing inductances/ p.u	1.483
Field resistance/ p.u	0.016
Field leakage inductance/ p.u	0.080
D-axis damping resistance/ p.u	0.052
D-axis leakage inductance/ p.u	0.060
Q-axis damping resistance/ p.u	0.052
Q-axis leakage inductance/ p.u	0.060

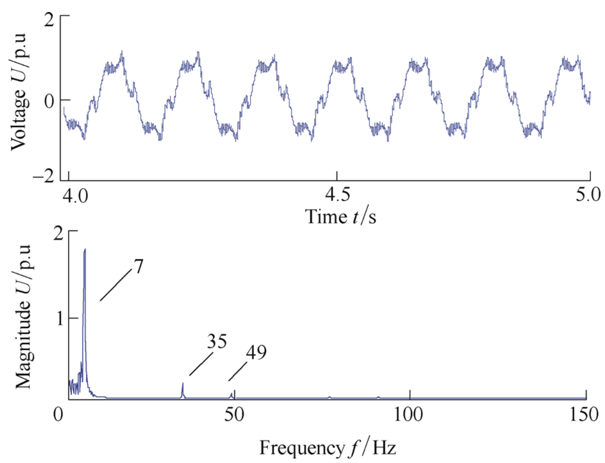


Fig. 5. Stator current waveform and spectrum

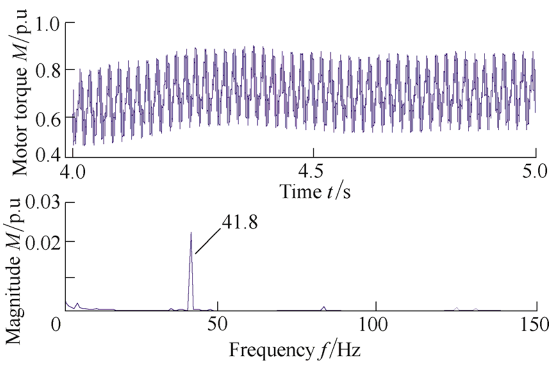


Fig. 6. Electromagnetic torque waveform and spectrum

$$\begin{cases} i_a = i_1 \sin(\omega t + \theta_1) + i_5 \sin(\omega t + \theta_5) + i_7 \sin(\omega t + \theta_7) + \cdots, \\ i_b = i_1 \sin\left(\omega t + \theta_1 - \frac{2\pi}{3}\right) + i_5 \sin\left(\omega t + \theta_5 - \frac{2\pi}{3}\right) + \\ \quad i_7 \sin\left(\omega t + \theta_7 - \frac{2\pi}{3}\right) + \cdots, \\ i_c = i_1 \sin\left(\omega t + \theta_1 + \frac{2\pi}{3}\right) + i_5 \sin\left(\omega t + \theta_5 + \frac{2\pi}{3}\right) + \\ \quad i_7 \sin\left(\omega t + \theta_7 + \frac{2\pi}{3}\right) + \cdots, \end{cases} \tag{1}$$

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ -\sin\omega t & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix}, \tag{2}$$

$$\begin{cases} \psi_d = L_{md}(i_d + i_f + i_D), \\ \psi_q = L_{mq}(i_q + i_Q), \end{cases} \tag{3}$$

$$T_e = \frac{3}{2} p \left(\psi_d i_q - \psi_q i_d\right). \tag{4}$$

Combining Eqs. (1)–(4), the electromagnetic torque can be simplified as

$$T_e = T_0 + T_1 \cos\left(6\omega t + \theta_a\right), \tag{5}$$

where i_1, i_5, i_7 —The 1st, 5th and 7th harmonic current,
$\theta_1, \theta_5, \theta_7$ —Starting phase angle of 1st, 5th and 7th harmonic curren,
ω —Synchronous speed,
i_q, i_d, i_f —Current of the q-axis ,d-axis and field,
i_D, i_Q —Damping current of d-axis and q-axis,
ψ_d, ψ_q —Flux linkage of d-axis and q-axis,
L_{md}, L_{mq}—Mutual inductance d-axis and q-axis,
T_e—Electromagnetic torque of motor,
p—Number of pairs of poles,
T_0—Steady value of ectromagnetic torque after simplification,
T_1—Electromagnetic torque resulting from harmonic current,
θ_a —Phase angle of T_1.

Eq. (5) shows that there is six times fundamental frequency component in the electromagnetic torque.

4 Characteristic of Mechanical Drive

To solve the natural frequency of the main drive mechanical system, according to the CAD drawings and parameters of rolling mill, finite element model is established by ANSYS(Fig. 7). The natural frequencies of the mechanical system are obtained and listed in Table 2. It is shown that the harmonic torque frequency (as shown in Fig. 6) is close to the second-order natural frequency of the main drive mechanical system. In the rolling process, mill main drive system is incented by multiple external loads. With the change of rolling speed, the adjusting frequency of drive motor also changes, according to the vibration theory, when the harmonic frequency of electric drive is close to the natural frequency of mechanical drive system, a strong torsional vibration of the main drive system is induced(as shown in Fig. 1(a)).

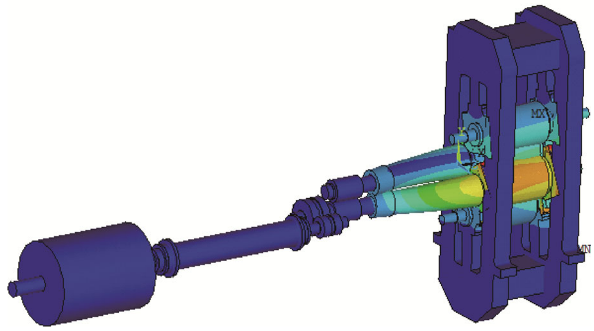


Fig. 7. Finite element model of mechanical drive system for F3 rolling mill

Table 2. Natural frequency of mechanical drive system for F3 rolling mill

Order of model	1	2	3	4	5	6	7
Frequence f/Hz	18.6	41.4	80.4	138	187	292	335

5 Mechanism of Electromechanical Coupling

When harmonic torque(42 Hz) is applied to rolling mill drive system, natural frequency is excited. The motor rotor speed is stable when vibration does not happen, when the modal frequency of mechanical drive system are excited, motor rotor speed contains natural frequency component. (Fig. 8)

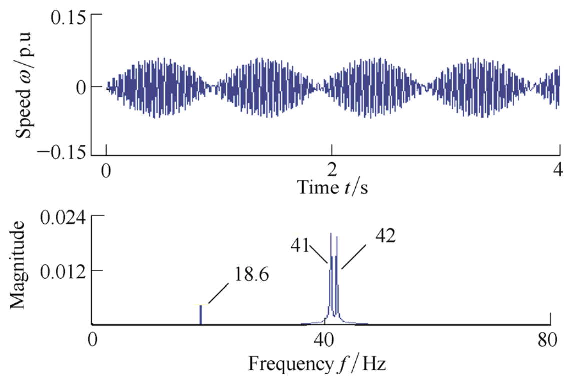


Fig. 8. Waveform and spectrum of revolving speed for motor

Due to the electromagnetic interactions, rotor speed oscillation cause stator current distortion[25–26], current distortion generates current harmonic which leads to torque harmonic, and the torque harmonic again contributes to the rotor speed fluctuation. so, the interaction is running between current harmonic and rotor speed which is expressed in Fig. 9.

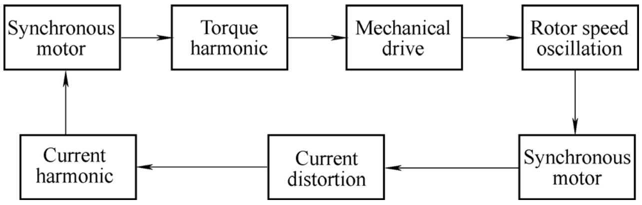
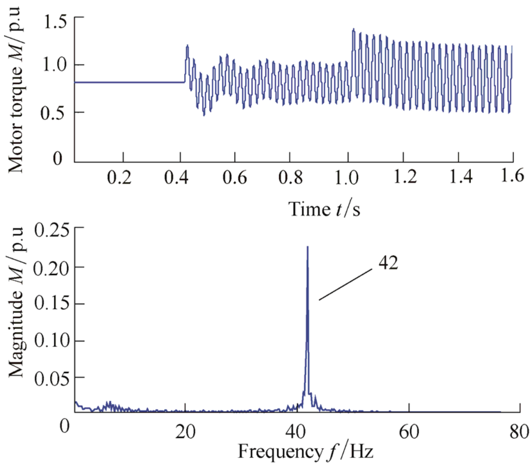
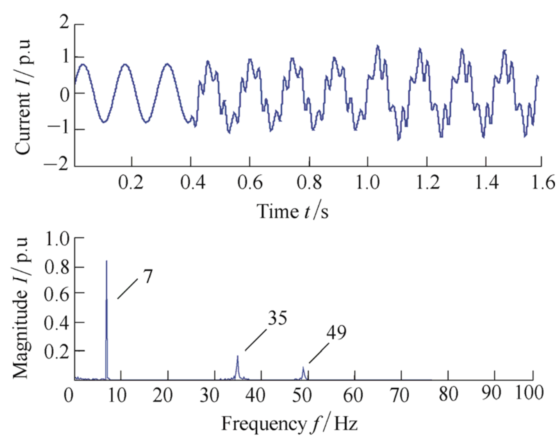


Fig. 9 Diagram of interaction for harmonic current and rotor speed

Using Matlab/Simulink simulation tool , Fig. 10 and Fig. 11 are obtained for explaining the process of coupling. In the case of 0–0.4 s of Fig. 10, the power supply is an ideal sinusoidal current，it can be seen that the motor output torque is a stable value in Fig. 10(a). In the case of 0.4–1 s, there are harmonic currents in power supply, it can be seen that corresponding motor output torque is oscillating. In the case of 1–2.2 s, the power supply for motor contains both harmonic currents and distortion currents generated by rotor speed oscillation, it can be seen that the motor output torque is oscillating at the frequence of 42 Hz and the oscillating amplitude is the largest in Fig. 10 and Fig. 11. In the case of 2.2–2.8 s, the power supply contains distortion currents without harmonic currents, it can be seen that motor output torque is also oscillating and the oscillating amplitude is smaller than the coupling case in Fig. 11.

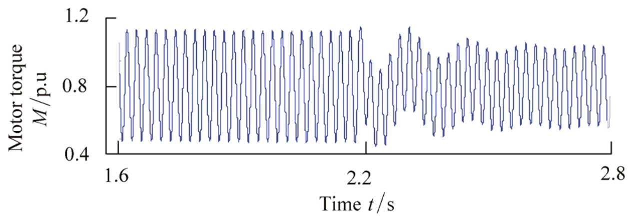


(a) Diagram of variation of motor torque

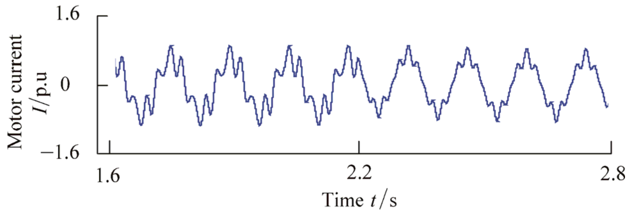


(b) Diagram of variation of motor current

Fig. 10 Diagram of variation of motor current and motor torque (0–1.6 s)



(a) Diagram of variation of motor torque



(b) Diagram of variation of motor current

Fig. 11 Diagram of variation of motor current and motor torque (1.6–2.8 s)

So, it can be seen from the above research that this coupling vibration behaviors affect the dynamic characteristic of main drive system, moreover, the nonlinear characteristics of mechanical drive system should be involved for the analysis of torsional vibration[27–29]

6 Nonlinear Characteristic Analysis for Mechanical Drive

To make clear the reason of vibration on the main drive system, researching nonlinear characteristics of mechanical drive system is necessary. In addition, for simplifing computation, according to the parameters of the finite element model in section 4, equivalent principle is used for calculating the inertia and stiffness of the simplified model. Finally, a model with nonlinear stiffness and damping for mechanical drive system is set up in Fig. 12

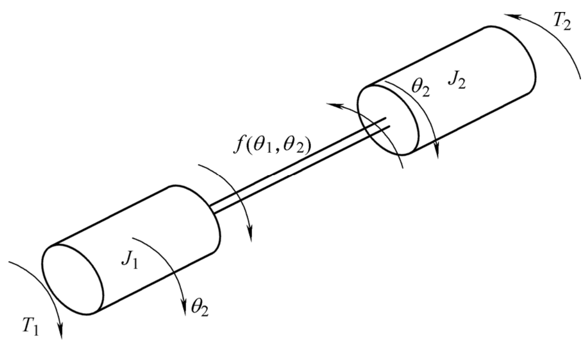


Fig. 12. Equivalent kinetic model for main drive mechanical structure

Applying Lagrange’s equations, the torsional vibration equations of the two degrees of freedom model including nonlinear damping and nonlinear stiffness can be written in the form:

$$\begin{cases} J_1\ddot{\theta}_1 + c_1\left(\dot{\theta}_1 - \dot{\theta}_2\right) + c_2\left(\dot{\theta}_1 - \dot{\theta}_2\right)^3 + k_1\left(\theta_1 - \theta_2\right) + \\ \quad k_2\left(\theta_1 - \theta_2\right)^3 = T_1, \\ J_2\ddot{\theta}_2 - c_1\left(\dot{\theta}_1 - \dot{\theta}_2\right) - c_2\left(\dot{\theta}_1 - \dot{\theta}_2\right)^3 - k_1\left(\theta_1 - \theta_2\right)^3 - \\ \quad k_2\left(\theta_1 - \theta_2\right)^3 = -T_2, \end{cases} \quad (6)$$

where J_1, J_2—Moment of inertia for motor and roller，
θ_1 , θ_2 —Angular displacement of motor and roller,
$\dot{\theta}_1$, $\dot{\theta}_2$ —The speed of the motor and roller,
k_1, k_2—Once and third power stiffness coefficient,
c_1, c_2—Once and third power damping coefficient,
T_1, T_2—Electromagnetic torque and load torque.

Assuming that:

$$T_1 = T_{10} + T_{11}\cos(\omega t + \alpha), \quad (7)$$

$$T_2 = T_{20} + T_{21}\cos(\omega t + \gamma), \quad (8)$$

where T_{10}—Steady-state value of electromagnetic torque,
T_{11}—Fluctuating value of electromagnetic torque,
ω —Fluctuations frequency,
T_{20}—Steady-state value of load torque,
T_{21}—Fluctuations value of load torque.

Because both the current harmonic and load fluctuation can excite the vibration of mill drive system described above, to simplify the analysis, the load fluctuation is ignored here, then Eq. (9) is effective in stable equilibrium condition:

$$T_2 = T_{10}. \quad (9)$$

The first formula of Eq. (1) is multiplied $1/J_1$, and the second formula of Eq. (1) is multiplied $1/J_2$, after subtraction of the two items, finally a nonlinear dynamic equation of one degrees of freedom is obtained in the form:

$$\ddot{x} + J(k_1x + c_1\dot{x}) + J(k_2x^3 + c_2\dot{x}^3) = JT_{10} + \frac{T_{12}}{J_1}\cos(\omega t + \alpha). \quad (10)$$

Let

$$x = \theta_1 - \theta_2,\ J = \frac{J_2 + J_1}{J_1J_2},\ a = \frac{J_2 + J_1}{J_1J_2}c_1,\ b = \frac{J_2 + J_1}{J_1J_2}c_2,$$
$$c = \frac{J_2 + J_1}{J_1J_2}k_2, m = \frac{J_2 + J_1}{J_1J_2}T_{10}, n = \frac{T_{11}}{J_1}T_{10}, \omega_0^2 = \frac{J_2 + J_1}{J_1J_2}k_1, \quad (11)$$

Eq. (10) can be written as

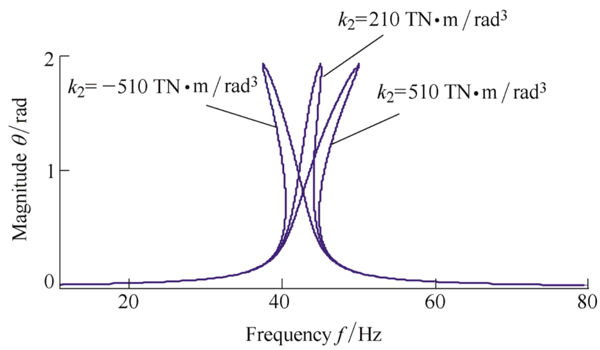
$$\ddot{x} + \omega_0^2x + a\dot{x} + b\dot{x}^3 + cx^3 = m + n\cos(\omega t + \alpha). \quad (12)$$

Eq. (12) can be used for solving the frequency response characteristics of mechanical drive, using averaging method to solve Eq. (12), amplitude-frequency equation of system is obtained in the form:

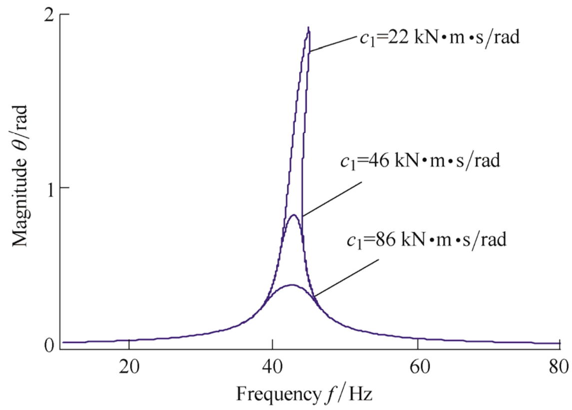
$$\left(\frac{3b\omega^3A^3}{4} + a\omega A\right)^2 + \left(\omega_0^2 - \omega^2 + \frac{3cA^3}{4}\right)^2 = n^2, \quad (13)$$

where A is amplitude of x.

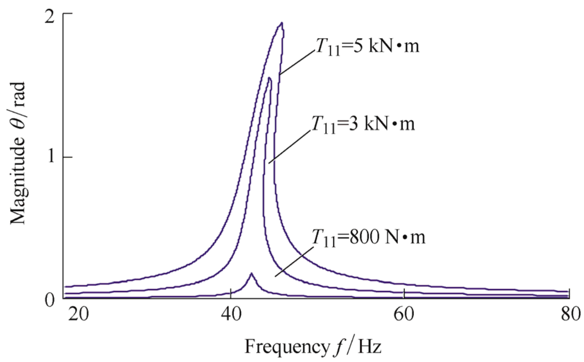
It can be seen from Eq. (13) that primary resonance is affected by damping term “a” and “b” ,stiffness term “c”, excitation frequency “ω” and the excitation amplitude term “n”. And base on numerical solutions of Eq. (13), the dynamic characteristics of mechanical drive system influenced by nonlinear factors can be analyzed. In terms of equivalent parameters(J_1=15 748 kg • m^2, J_2=12 500 kg • m^2, k_1=485 MN • m/rad, k_2=510 TN • m/rad^3, c_1=22 kN • m • s/rad, c_2=120 N • m • s^3/rad^3, T_{11}=3000 N • m), the value of a, b, c, and n are calculated and substituted into Eq. (13) for numerical simulation. Vibration amplitude of rolling mill changes with parameter variation as shown in Fig. 13.



(a) Variation of stiffness coefficient



(b) Variation of damping coefficient



(c) Variation of amplitude of electromagnetic torque

Fig. 13. Characteristic diagram of vibration amplitude changes with parameter variation

Fig. 13(a) shows that the frequency response curve bend from the left to the right when the third power nonlinear stiffness change from negative to positive, in this case, jump phenomena of amplitude appear. This illustrates nonlinear stiffness has an effect on vibration amplitude. When the external harmonic excitation, whose frequency is close to the system natural frequency, make effect on the main drive system—a nonlinear system, the variation of stiffness make the main resonance amplitude change, and the strong and weak torsional vibration occur on the main drive shaft of rolling mill. Fig. 13(b) shows that vibration amplitude decreases when the value of nonlinear damping term increases, and it is not obvious to observe the jump phenomenon of magnitude. This illustrates increasing the damping is beneficial for vibration suppression. Therefore, it can be considered that the structural material of large damping is used to reduce resonant responce on driveline components of main drive system. Fig. 13(c) shows that vibration amplitude decreases accordingly when the excitation amplitude decreasing. This illustrates decreasing incentives is effective for restraining vibration. For the main drive system of rolling mill, the problems to be solved urgently are enhancing the quality of the electrical power system as far as possible, reducing harmonic interference in the drive system and developing a highly efficient "green" inverter.

The analysis of vibration characteristics is the basis of research of coupling vibration as follows.

7 Comprehensive analysis of Characteristics for Torsional Vibration

In the process of production, harmonic frequency of power supply changes with the speed variation. When excitation frequency of harmonic torque is close to the natural frequency of mechanical drive system, beat vibration appear obviously(Fig. 1(b)).

In Fig. 14, horizontal axis denotes variable frequency of motor inverter, and vertical axis denotes distribution of nature frequency for mechanical drive system. Variable frequency range of motor generally is about 6 to 11 Hz when rolling. Fig. 14 shows that harmonic frequency within the scope of tag is coupling with the second order natural frequency exactly.

When coupling vibration occurs, the beat vibration is different from ideal vibration of constant amplitude(Fig. 8) under the influence of nonlinear stiffness and damping of transmission structure, it may be shown as in Fig. 1(b). When the harmonic torque frequency and the second order natural frequency of mechanical drive system are same, strong resonance appears(Fig. 1(a)).

8 Conclusions

(1) The vibration signals of main drive system indicate that mill vibration has the electromechanical coupling and nonlinear dynamic characteristics.

(2) There is the connection in the output of cycloconverter, synchronous motor and mechanical drive system. The current distortion can result in the pulsating torque of motor output and the speed oscillation can produce the current distortion in electrical system.

(3) The nonlinear dynamic analysis of mechanical drive system shows that the vibraton magnitude are influenced by the stiffness, damping coefficient and the electromagnetic torque.

(4) Restraining mill vibration needs to endeavour from two aspects of electrical and mechanical system.

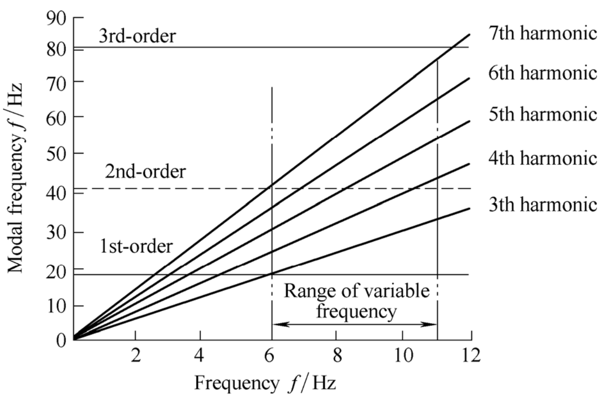


Fig. 14. Diagram for coupling of variable frequency harmonic and modal frequency of main drive system

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