

Analysis of electromechanical coupling facts of complicated electromechanical system^①

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[Abstract] From aspect of electromechanical coupling, the probable conditions that cause rolling mill chatter to lead to periodic thickness error or bring about light and shade streaks on the surface of steel strip were studied. CM04 temper mill, a typical complicated electromechanical system, was taken as object of study to explore electromechanical coupling facts in complicated electromechanical system. Four modes of electromechanical coupling and their acting principle and law were expounded. Some suggests and measures were put forward for designing of a class of complicated electromechanical system.

[Key words] complicated electromechanical system; electromechanical coupling; electromagnetic torque; harmonic torque; micro-variable control

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1 INTRODUCTION

Complicated electromechanical system is such a system which includes multiple physical processes, implement diverse energy conveying and converting by means of multi-element and multi-dimension motions, and whose main motion is regulated and controlled by information stream of micro-control variables^[1]. This kind of system is used widely in industrial, scientific and technological fields, and plays an important role in the development of national economy. Like four-high or multi-high cold rolling mill, continual rolling mill, electric locomotive, high-speed magnetic suspension locomotive, industrial robot, intelligent robot and so on, they integrate mechanical, electrical, hydraulic, automatic and computer technologies in themselves, implement their functions by means of multi-physical processes, and should belong to great-size and high-tech complicated electromechanical system. Generally speaking, there exist mutual actions of electromechanical parameters, rigid-elastic parameters, fluid-solid parameters and thermo-elastic parameters in complicated electromechanical system. That is to say, there are diverse coupling actions such as electromechanical coupling, rigid-elastic coupling, fluid-solid coupling, thermo-elastic coupling and so on in complicated electromechanical system. The key to the question of dynamic modeling, dynamic characteristic analysis, decoupling design, operating mode monitor, troubleshoot diagnosis and warn of complicated electromechanical system is to fully recognize and quantitatively analyze these coupling effects^[2].

In complicated electromechanical system, there are four electromechanical coupling modes: 1) electromagnetic torque direct coupling; 2) harmonic torque direct coupling^[3]; 3) micro-variable control loop coupling; 4) multi-driving system coupling by workpiece. This paper takes CM04 temper mill, a typical complicated electromechanical system, as a object of study to explore electromechanical coupling facts in complicated electromechanical system, analyzes its coupling principles and laws in order to probe into probable conditions that cause rolling mill chatter to lead to periodic thickness error or light and shade streaks on surface of steel strip from aspect of electromechanical coupling^[4].

2 ELECTROMAGNETIC TORQUE DIRECT COUPLING

Electromechanical torque direct coupling is a basic mode of electromechanical coupling^[5]. Electromechanical torque produced by mutual action of electromagnetic field drives working machine through driving apparatus, and implements design functions by controlling motion form, state, and trace of working machine. The physical process of coupling mode can be described by electromagnetic torque equation and dynamic equation of driving system.

The electromagnetic torque equation is

$$M_d = C_m \Phi_d \quad (1)$$

where M_d —electromagnetic torque, C_m —structural constant, Φ —magnetic flux, I_d —armature current.

The dynamic equation is

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$$M_d - M_{fz} = \frac{GD^2}{375} \cdot \frac{dn_d}{dt} \quad (2)$$

where M_{fz} —equivalent load torque in shaft of electric motor, n_d —rotating speed of electric motor, GD^2 —total flywheel torque.

The main electric motor of CM04 temper mill drives working roller to level steel strip. The winding reel and the pay-off reel are driven respectively by their electric motors. They produce tensile force and keep it constant when CM04 temper mill works.

3 HARMONIC TORQUE DIRECT COUPLING

Modern electrical driving systems, whether DC driving systems or AC driving systems, are all supplied with power by SCR (silicon controlled rectifier). Hence, there always exists harmonic current in main loop of electric motor. The number of times and intensity of harmonic current are decided by circuit structure and wiring mode.

The driving motors of working roller, winding reel and pay-off reel of CM04 temper mill are all supplied with power by three-phase bridge SCR. The harmonic current Δi_d is expressed as

$$\Delta i_d = \sum_{j=6}^{\infty} I_{jm} \cos(j\omega t - \theta_j) \quad (3)$$

where I_{jm} —peak value of harmonic current, $j = 6, 12, 18, \dots$, i. e. there are 6 times (300Hz), 12 times (600Hz), 18 times (900Hz) and so on harmonic current in main loop of electric motor.

The frequency spectrum is obtained by testing time-domain signals of current in main loop of working roller electric motor and analyzing their frequency spectra after worksite experiment as shown in Fig. 1. It is very obvious that the spectrum peaks of 300Hz, 600Hz and 900Hz signals exist in Fig. 1. The experimental result is consistent with theoretic analysis.

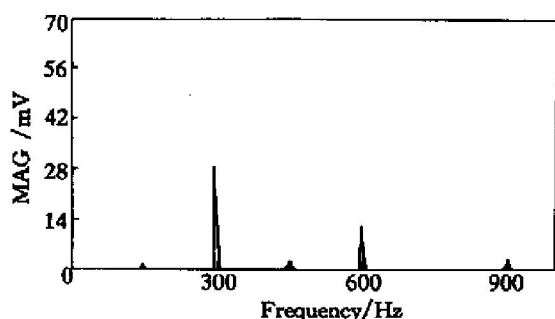


Fig. 1 Current frequency spectrum of main driving electric motor

Theoretically speaking, the above harmonic currents will reflect in main driving shaft in form of harmonic torques by energy-force conversion of electromagnetic field between stator and armature.

The harmonic torque can be expressed as:

$$\Delta M_a = C_m \phi \sum_{j=6}^{\infty} I_{jm} \cos(j\omega t - \theta_j) \quad (4)$$

The frequency spectrum is acquired by testing the torsional vibration signals of main driving shaft of working roller and analyzing their frequency spectra after worksite experiment as shown in Fig. 2. It is very clear that the spectrum peaks of 300Hz, 600Hz and 900Hz torsional vibration signals exist in Fig. 2.

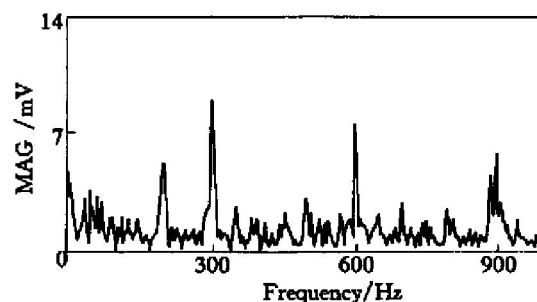


Fig. 2 Torsional signal frequency spectrum of main driving shaft

The facts prove that harmonic electromagnetic torques exist indeed in main driving shaft when CM04 temper mill works. Hence, it can be concluded that harmonic current in armature loop of main electric motor is direct impelling source of torsional vibration signal in main driving shaft.

Assume that load torque is constant, electromagnetic torque dynamics equation is expressed as

$$\Delta M_a = 2(J_h + J_m) \cdot \frac{1}{D} \cdot \frac{dv}{dt} \quad (5)$$

where J_h —mechanical rotating inertia, J_m —rotating inertia of electric motor, D —roller diameter, v —rolling velocity.

It is known from Eqn. (5) that if electromagnetic torque undulates, the rolling velocity also rises and falls in pace with it, which will cause fluctuation of tensile stresses, and lead to the work status of temper mill being unstable at last.

Therefore, it can be concluded that harmonic current in armature loop of main electric motor of modern high-speed rolling mill produces electromechanical coupling by electromagnetic field between stator and rotor, and the coupling effect influences dynamic characteristics of electrical driving system.

4 MICRO-VARIABLE CONTROL LOOP COUPLING

In electrical driving system of CM04 temper mill, the velocity control systems are all typical two-closed-loop regulating systems. The inner is current regulating loop, and the outer is velocity control loop. The velocity regulator (ST) and the current regulator (LT) are PI controllers. The control principle diagram is illustrated as shown in Fig. 3.

The harmonic current can be regarded as a disturbance. It gets into speed-adjusting system via current feedback units, and is amplified by current regu-

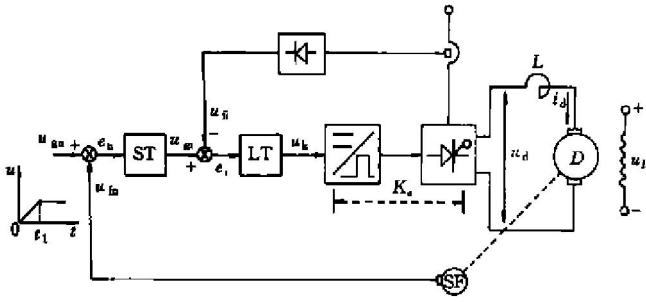


Fig. 3 Principle diagram of electrical driving subsystem of winding reel

lator, then acts on mechanical main motion.

Let effective harmonic current be I_i , its feed-back voltage is expressed as

$$\Delta u_{fi} = \beta_i I_i \quad (6)$$

where β_i —current feedback coefficient.

Through feedback correcting circuit as shown in Fig. 4, the feedback voltage signal is expressed as

$$\Delta u'_{fi} = \frac{x_c}{\sqrt{R_1^2 + x_c^2}} \Delta u_{fi} \quad (7)$$

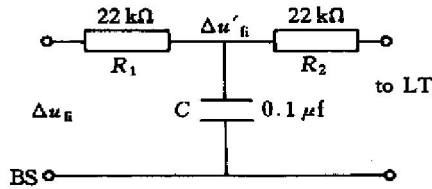


Fig. 4 Feedback correcting circuit

where $x_c = 2\pi f_j c$, i. e., capacitive reactance of C , and f_j is frequency of harmonic current.

Assume that the effective voltage of feedback signal is ΔU_{fi} , it is input to LT. The output voltage Δu_k of LT is

$$\Delta u_k = K_I (\Delta U_{fi} + \frac{1}{T_I} \int_0^{T_I} \Delta U_{fi} dt) \quad (8)$$

where K_I —proportion gain of LT, T_I —integral time constant of LT.

Because Δu_k causes trigger angle variation, the rectifying voltage increment is

$$\Delta u_d = K_a \Delta u_k \quad (9)$$

where K_a —coefficient of rectifying circuit.

The state space model of speed-regulating system is expressed as

$$\begin{bmatrix} \frac{dn}{dt} \\ \frac{d\Delta i_d}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{375 C_m \phi}{GD^2} \\ -\frac{C_e \phi}{L} & -\frac{R_\Sigma}{L} \end{bmatrix} \begin{bmatrix} n \\ \Delta i_d \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} \Delta u_d \quad (10)$$

where (aiming at CM04 temper mill) $C_e \phi = 1.03$, $C_m \phi = 9.5$, $R_\Sigma = 0.035 \Omega$, $L = 0.6 \text{ mH}$, $GD^2 = 1.99 \times 10^5 \text{ Nm}$.

From Eqn. (10), the current increment Δi_d of armature circuit can be worked out as following

$$\Delta i_d = 30.1 \Delta u_d (e^{-0.55t} - e^{-57.75t}) \quad (11)$$

For example, in a operating mode of CM04 temper mill, the average current of work roller is 699A, the measuring value of 600Hz harmonic current is 45A, in terms of Eqns. (6) ~ (9), Δu_d can be computed, $\Delta u_d = 21.6 \text{ V}$. Thus, at 3.3 ms, current increment Δi_d is 111.5 A. It results in great variation of electromagnetic torque, then causes considerable fluctuation of forth and back tensile stress, probably leads to indentations in strip steel.

5 MULTI-DRIVING SYSTEMS COUPLING BY WORKPIECE

The coupling mode exists universally in a class of complicated electromechanical system such as cold rolling mill, continual rolling mill, electric locomotive and so on. Three subsystems (pay-off reel, stand and winding reel) of CM04 temper mill are joined together with steel strip. The overall model of electrical driving system can be constructed by choosing forward and backward tensions as coupling variables. On considering that the STs of winding reel and pay-off reel is saturated when CM04 temper mill runs stably, and the minor time constants in feedback loops of current and speed can be ignored according to time-scale^[6] principle. The simplified system model^[7] is

$$\dot{X} = AX + BU + D \quad (12)$$

where $\dot{X} = [\dot{x}_1 \ \dot{x}_2 \ \dots \ \dot{x}_{12}]^T$; $X = [x_1 \ x_2 \ \dots \ x_{12}]^T$; x_3 , x_7 and x_{10} express respectively velocities of winding reel, working roller and pay-off reel; x_2 , x_6 and x_9 represent respectively currents of winding reel, working roller and pay-off reel; x_1 , x_5 and x_8 indicate respectively LT outputs of winding reel, working roller and pay-off reel; x_4 stands for ST output of working roller; x_{11} and x_{12} show respectively forward tension and backward tension; B is 12×12 control matrix; U is 12×1 input vector; D is 12×1 disturbance vector; A is system matrix described as Eqn. (13).

Note that some of non-zero parameters $a_{i,j}$ in A are purely mechanical parameters, some of them are purely electrical parameters, and others are electromechanically mixed parameters, that is to say, the electro-mechanical parameters are mutually osmotic or coupling. In addition, the parameters closed by dotted-line frame in main diagonal line of matrix A belong respectively to winding reel subsystem, stand subsystem and pay-off reel subsystem from top to bottom, and the lowest two row and the rightest twoline parameters in A are forward and backward tension coefficients. It is easily understood that the parameters or state variables of the three subsystems are mutually coupled by forward and backward tension. Their coupling path is shown as Fig. 5.

According to Eqn. (12) and Fig. 5, we can ana

$$A = \begin{bmatrix} 0 & a_{1,2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{2,1} & a_{2,2} & a_{2,3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{3,2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{3,11} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{4,7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{5,4} & 0 & a_{5,6} & a_{5,7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{6,4} & a_{6,5} & a_{6,6} & a_{6,7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{7,6} & 0 & 0 & 0 & 0 & a_{7,11} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{8,9} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{9,8} & a_{9,9} & a_{9,10} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{10,9} & 0 & 0 & a_{10,12} \\ 0 & 0 & a_{11,3} & 0 & 0 & 0 & a_{11,7} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{12,7} & 0 & 0 & a_{12,10} & 0 & 0 \end{bmatrix} \quad (13)$$

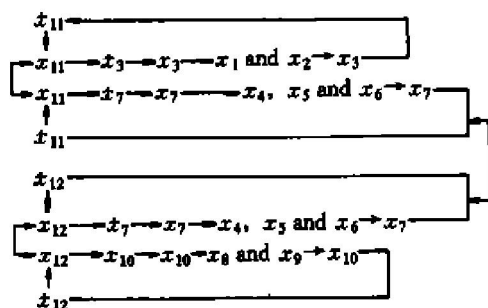


Fig. 5 Coupling path of parameters

lyze qualitatively and quantitatively the dynamic characteristics of electric driving system of CM04 temper mill^[3], can also research system's response to instruction of rolling speed and disturbances by simulation, and can still compute and analyze varying trend curves of forward and backward tensions^[7].

6 CONCLUSION

The electromechanical system consisted of control system, electrical driving system, mechanical driving apparatus, function implementation devices and so on is quite complicated because direct and indirect coupling actions exist among the parts. The above-mentioned four modes of electromechanical coupling act and influence each other so that they change the dynamic and static performances of system. The key to the question of removing the crossed-coupling influence is that we must recognize fully electromechanical coupling principle and law, construct an overall electromechanical coupling parameters model. By decoupling design^[8,9], parameter optimization and robust control^[10~12], it is believable that the whole system can run in optimum state.

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