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Modeling for driving systems of four-high rolling mill①

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[Abstract] A modeling method for driving systems of four-high rolling mill was put forward in order to analyze the origin of rolling mill's chatter that brings about light and shade streaks on the surface of steel strip from aspect of electromechanical coupling. The process and steps of modeling method was introduced by means of an example. The correctness of the model and the feasibility of the modeling method were verified in simulation experiment.

[Key words] modeling; rolling mill; driving system; electromechanical coupling

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1 INTRODUCTION

Four-high rolling mill is widely used in processing of steel and nonferrous metal. It integrates mechanical, electrical, hydraulic and automatic technologies, and accomplishs leveling and processing of metal plate and strip. It belongs to large-scale and advanced-technology complicated electromechanical system[1]. Studying on modeling of the system can contribute to analyzing origin of rolling mill's chatter[2, 3] which brings about light and shade streaks[4] on the surface of steel strip from aspect of electromechanical coupling[5]. So far, many scholars have done a lot of researching work around the significant subject and from its different aspects and achieved some important breakthroughs[6~ 9]. Through constructing mathematical model of CM04 temper mill, this paper presents a coupling modeling method for driving system of four-high roll mill, expounds modeling process and steps, engages in simulation experiment, and acquires a consistent result with the reality.

2 CONSTRUCTION OF COUPLING MODEL

2.1 Coupling modeling train of thought

Most of four-high rolling mills consist of many units or subsystems whose structures, mechanical characteristics and electrical characteristics are basically similar. Each subsystem is mutually independent and non-interference when it doesn't take part in processing metal plate and strip, so their mathematical models can be constructed respectively according to dynamic principle. For example, when CM04 temper mill levels steel strip, the workpiece joins together independent subsystem to be a complicated coupling system. As a result of conveying and fluctuating of coupling force, the mutual coupling subsystems will interfere each other, and their dynamic characteristics will be affected. It is very clear from Fig. 1 that the coupling variables between electromechanical driving subsystems are forward and backward tension forces, so the coupling dynamic model of the whole system can be constructed according to calculating method and conveying regulation of forward and backward tension forces.

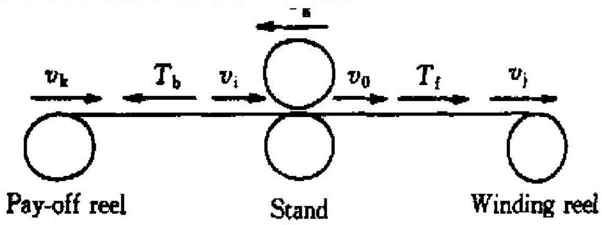

Fig. 1 Rolling demonstration diagram of temper mill

2.2 Dynamic model of CM04 temper mill subsystem

CM04 temper mill consists of three electromechanical driving subsystems, i. e. winding reel, stand and pay-off reel. The structure and dynamic characteristics of the three subsystem are quite similar. The following will take a example of winding reel to introduce subsystems' modeling process and steps. The electrical driving system of the winding reel is a typical 2-closed-loop tuning speed system, its structural diagram is shown as Fig. 2. It consists of speed regulator (PI), current regulator (PI), trigger, silicon-controlled rectifier (SCR), armature circuit of motor, speed-feedback circuit and current-feedback circuit.

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The transfer function diagram of Fig. 2 is shown as Fig. 3. Fig. 3 can be redone the state variable diagram (omitted). In the state variable diagram, the state variables x_1, x_2, x_3, x_4, x_5, x_6 and x_7 are successively defined as output signals of integrators. The dynamic model of the winding reel may be written as differential equation cluster:

$$\left.\begin{aligned}
\dot{x}_1 &= -\frac{\beta_{jn}}{T_{jfn}}x_7 + U_{jgn}\\
\dot{x}_2 &= \frac{K_{js}}{T_{jIs}}x_1 - \frac{\beta_{ji}}{T_{jfi}}x_6 - \frac{K_{js}\beta_{jn}}{T_{fn}}x_7 + K_{js}U_{jgn}\\
\dot{x}_3 &= \frac{K_{js}K_{ji}}{T_{jIs}}x_1 + \frac{K_{ji}}{T_{jIi}}x_2 - \frac{K_{ji}\beta_{ji}}{T_{jfi}}x_6 - \frac{K_{js}K_{ji}}{T_{jfn}}x_7 + K_{js}K_{ji}U_{jgn}\\
\dot{x}_4 &= \frac{K_{ja}}{T_{ja}}x_3 - \frac{R_{j\Sigma}}{L_j}x_4 - \frac{375K_{je}}{GD_j^2}x_5\\
\dot{x}_5 &= \frac{K_{jm}}{L_j}x_4 - M_{jfz}\\
\dot{x}_6 &= \frac{1}{L_j}x_4 - \frac{1}{T_{jfi}}x_6\\
\dot{x}_7 &= \frac{375}{GD_j^2}x_5 - \frac{1}{T_{jfi}}x_7
\end{aligned}\right\} \qquad (1)$$

where U_{jgn} —given speed signal, K_{js} —proportion gain of speed regulator, T_{jIs} —integral time of speed regulator, K_{ji} —proportion gain of current regulator, T_{jIi} —integral time of current regulator, K_{ja} —coefficient of rectifier, T_{ja} —delay time of rectifier, $R_{j\Sigma}$ —total resistance in armature circuit, K_{jm} —torque constant of motor, GD_j^2 —total rotating inertia in axis of motor, K_{je} —coefficient of electric potential energy, M_{jfz} —torque of load, β_{jn} —speed feedback coefficient, T_{jfn} —time constant in speed feedback circuit, β_{ji} —current feedback coefficient, T_{jfi} —time constant in current feedback circuit.

Similarly, the dynamic models of the stand subsystem and the pay-off reel subsystem can be constructed. They are respectively expressed as differential equation Eqns. (2) and (3). The names and symbols of parameters in Eqn. (2) and Eqn. (3) are respectively corresponding with ones in Eqn. (1).

$$\left.\begin{aligned}
\dot{x}_8 &= -\frac{\beta_{gn}}{T_{gfn}}x_{14} + U_{ggn}\\
\dot{x}_9 &= \frac{K_{gs}}{T_{gIs}}x_8 - \frac{\beta_{gi}}{T_{gfi}}x_{13} - \frac{K_{gs}\beta_{gn}}{T_{gfn}}x_{14} + K_{gs}U_{ggn}\\
\dot{x}_{10} &= \frac{K_{gs}K_{gi}}{T_{gIs}}x_8 + \frac{K_{gi}}{T_{gIi}}x_9 - \frac{K_{gi}\beta_{gi}}{T_{gfi}}x_{13} - \frac{K_{gs}K_{gi}}{T_{gfn}}x_{14} + K_{gs}K_{gi}U_{ggn}\\
\dot{x}_{11} &= \frac{K_{ga}}{T_{ga}}x_{10} - \frac{R_{g\Sigma}}{L_g}x_{11} - \frac{375K_{ge}}{GD_g^2}x_{12}\\
\dot{x}_{12} &= \frac{K_{gm}}{L_g}x_{11} - M_{gfz}\\
\dot{x}_{13} &= \frac{1}{L_g}x_{11} - \frac{1}{T_{gfi}}x_{13}\\
\dot{x}_{14} &= \frac{375}{GD_g^2}x_{12} - \frac{1}{T_{gfi}}x_{14}
\end{aligned}\right\} \qquad (2)$$

$$\left.\begin{aligned}
\dot{x}_{15} &= -\frac{\beta_{kn}}{T_{kfn}}x_{21} + U_{kgn}\\
\dot{x}_{16} &= \frac{K_{ks}}{T_{kIs}}x_{15} - \frac{\beta_{ki}}{T_{kfi}}x_{20} - \frac{K_{ks}\beta_{kn}}{T_{kfn}}x_{21} + K_{ks}U_{kgn}\\
\dot{x}_{17} &= \frac{K_{ks}K_{ki}}{T_{kIs}}x_{15} + \frac{K_{ki}}{T_{kIi}}x_{16} - \frac{K_{ki}\beta_{ki}}{T_{kfi}}x_{20} - \frac{K_{ks}K_{ki}}{T_{kfn}}x_{21} + K_{ks}K_{ki}U_{kgn}\\
\dot{x}_{18} &= \frac{K_{ka}}{T_{ka}}x_{17} - \frac{R_{k\Sigma}}{L_k}x_{18} - \frac{375K_{ke}}{GD_k^2}x_{19}\\
\dot{x}_{19} &= \frac{K_{km}}{L_k}x_{18} - M_{kfz}\\
\dot{x}_{20} &= \frac{1}{L_k}x_{18} - \frac{1}{T_{kfi}}x_{20}\\
\dot{x}_{21} &= \frac{375}{GD_k^2}x_{19} - \frac{1}{T_{kfi}}x_{21}
\end{aligned}\right\} \qquad (3)$$

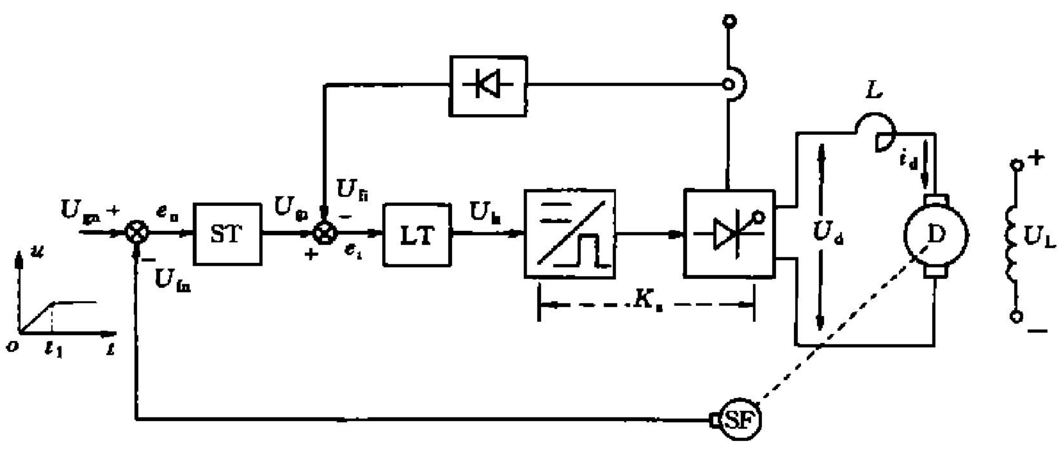

Fig. 2 Principle diagram of electrical driving subsystem of winding reel

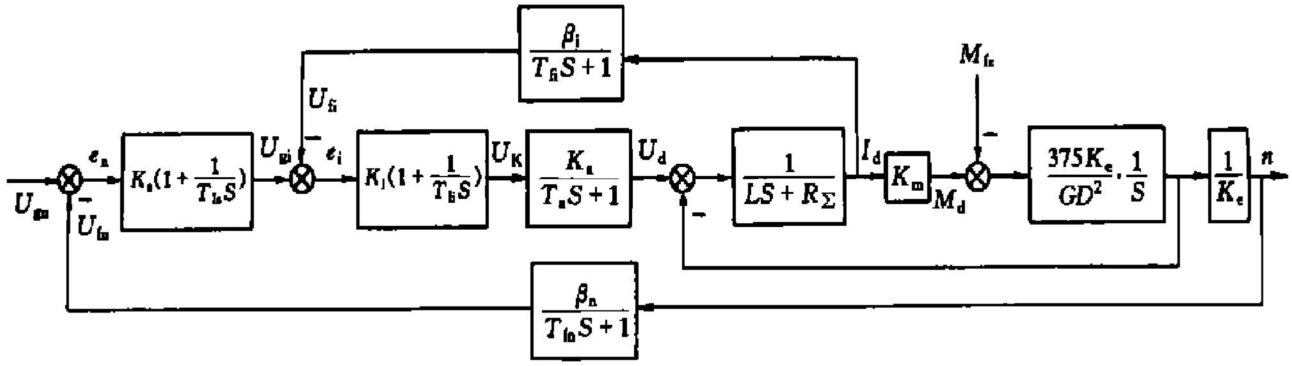

Fig. 3 Transfer function diagram of winding reel subsystem

2.3 Overall model of electromechanical driving system of CM04 temper mill

In rolling or leveling process, steel strip joins together the winding reel, the stand and the pay-off reel, the coupling structure is shown as Fig. 1.

On condition that n_j, n_g and n_k are rotating speed of winding reel, stand and pay-off reel respectively; i_j, i_g and i_k are drive ratio of winding reel, stand and pay-off reel respectively; r_j is radius of steel roll in the winding reel, r_g is radius of the roller, and r_k is radius of steel roll in the pay-off reel. The following expressions are acquired from Fig. 3:

$$n_j = \frac{375}{GD_j^2} x_5 \tag{4}$$

$$n_g = \frac{375}{GD_g^2} x_{12} \tag{5}$$

$$n_k = \frac{375}{GD_k^2} x_{19} \tag{6}$$

The following expressions are linear velocity of winding reel, stand and pay-off reel.

$$v_j = r_j n_j / i_j \tag{7}$$

$$v_g = r_g n_g / i_g \tag{8}$$

$$v_k = r_k n_k / i_k \tag{9}$$

The following expressions are output and input velocity of the stand.

$$v_o = (1 + S_f) v_g \tag{10}$$

$$v_i = (1 - S_b) v_g \tag{11}$$

where S_f is the forward sliding coefficient of steel strip in the stand, S_b is the backward sliding coefficient.

The forward tension force[10] is expressed as

$$T_f = \frac{A_f E}{L_f} \int (v_j - v_o) \mathrm{d}t \tag{12}$$

The backward tension force[10] is expressed as

$$T_b = \frac{A_b E}{L_b} \int (v_i - v_k) \mathrm{d}t \tag{13}$$

where A_b is the crosscut area of input steel strip, A_f is the crosscut area of output steel strip, L_b is the length of steel strip between the pay-off reel and stand, L_f is the length of steel strip between the stand and the winding reel, and E is elastic modulus of steel strip. Let state variable $x_{22} = T_f$, $x_{23} = T_b$, the differential equations are obtained from Eqns. (4) ~ (13).

$$\dot{x}_{22} = \frac{375 A_f E r_j}{GD_j^2 L_f i_j} x_5 - \frac{375 A_f E (1 + S_f) r_g}{GD_j^2 L_f i_g} x_{12} \tag{14}$$

$$\dot{x}_{23} = \frac{375 A_b E (1 - S_b) r_g}{GD_g^2 L_b i_g} x_{12} - \frac{375 A_b E r_k}{GD_k^2 L_b i_k} x_{19} \tag{15}$$

In the differential equation cluster (1), the load torque M_{jfz} includes friction torque M_{jf}, and the forward tension force torque M_{jTf}. Their relation is described as

$$M_{jfz} = M_{jf} + M_{jTf} = f_j n_j + \frac{r_j T_f}{i_j} = \frac{375 f_j}{GD_j^2} x_5 + \frac{r_j}{i_j} x_{22} \tag{16}$$

where f_j is friction coefficient.

In the differential equation cluster (2), the load torque M_{gfz} includes friction torque M_{gf}, the forward tension force torque M_{gTf} and the backward tension force torque. Their relation is described as

$$\begin{aligned} M_{gfz} &= M_{gf} - M_{gTf} + M_{gTb} \\ &= f_g n_g - \frac{r_g T_f}{i_g} + \frac{r_g T_b}{i_g} \\ &= \frac{375 f_g}{GD_g^2} x_{12} - \frac{r_g}{i_g} x_{22} + \frac{r_g}{i_g} x_{23} \end{aligned} \tag{17}$$

where f_g is friction coefficient.

In the differential equation cluster (3), the load torque M_{kfz} includes friction torque M_{kf} and the forward tension force torque M_{kTb}. Their relation is described as

$$M_{kfz} = M_{kf} - M_{kTb} = f_k n_k - \frac{r_k T_f}{i_k} = \frac{375 f_k}{GD_k^2} x_{19} - \frac{r_k}{i_k} x_{23} \tag{18}$$

where f_k is friction coefficient.

Let Eqns. (16), (17) and (18) substitute respectively into M_{jfz} in Eq. (1), M_{gfz} in Eqn. (2) and M_{kfz} in Eqn. (3). Therefore, the overall dynamic model consisting of Eqns. (1), (2), (3), (14) and (15) can be obtained. It is easily written to state space model (omitted).

3 REDUCTION AND SIMULATION OF SYSTEM MODEL

3.1 Model reduction approach

Four-high rolling mill is comparatively complicated system consisted of many stands or units. The order of model constructed by the above-mentioned method is fairly high. It will bring about many troubles to system model simulation and optimization design. Sometimes, this work is even unable to be done. Therefore, a model reduction approach is proposed under the condition of retaining main eigenvalues values and significant state variables of original system. It is just to ignore some minor time constants according to time-scale principle[11]. Specifically speaking, because the delay of SCR and the time constants in the current and speed feedback circuit are far less than those in main circuit and electromechanical time constants, they can be ignored when constructing overall model. For example, in the above-constructed dynamic model of CM04 temper mill, T_{jfi}, T_{jfn}, T_{ja}, T_{gfi}, T_{gfn}, T_{ga}, T_{kfi}, T_{kfn} and T_{ka} may be nullified. In addition, when CM04 temper mill works normally, the speed regulators in the electrical driving control systems of the winding reel and the pay-off reel are saturated, that is to say, the speed loops are open. In this case, system's model can be simplified greatly. The order of model is reduced from 23 to 12. It will bring about much convenience to finding the solution of model, analyzing and designing system.

3.2 Model simulation

Let the actual parameter values of CM04 temper mill substitute into the above-constructed mathematical model, and the model is simulated[12] by means of MATAB 5.3 language. When the input is step signal, the dynamic curves of the rotating speed n_j, n_g and n_k are displayed as Fig. 4. The dynamic curves of

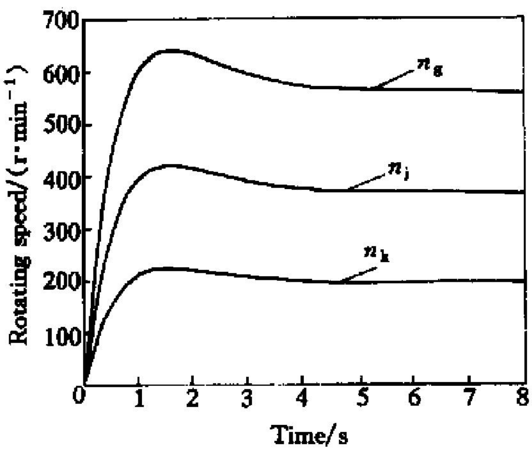

Fig. 4 Dynamic curves of rotating speeds

deviation ΔT_f and ΔT_b of tension force T_f and T_b are shown as Fig. 5 and Fig. 6. It is visible that the simulating results are basically consistent with reality. Thus, the model is correct, and it is probable to analyze causes that bring about light and shade streaks on the surface of steel strip processed by CM04 temper mill and design an optimum controller for CM04 temper mill based on the model.

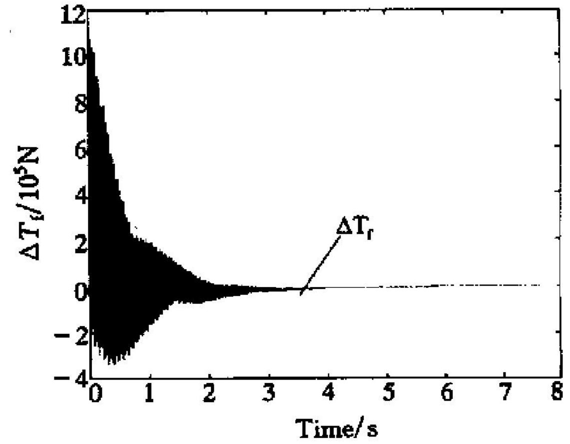

Fig. 5 Dynamic curves of deviation ΔT_f

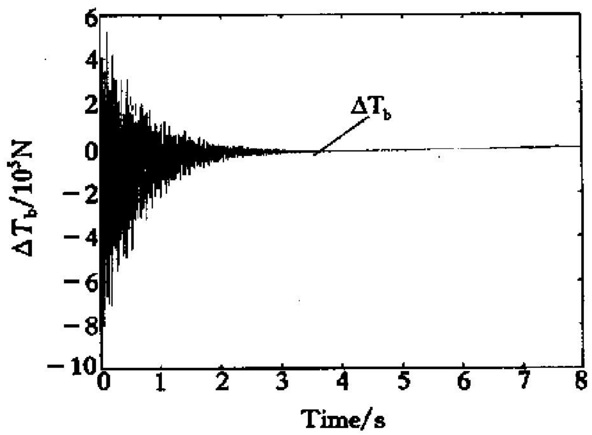

Fig. 6 Dynamic curves of deviation ΔT_b

4 CONCLUSION

Aiming at four-high rolling mill, the following steps are applied to constructing the coupling mathematical model of electromechanical driving system. Firstly, the mathematical model of each electrical driving subsystem is constructed by means of modeling method of structural principle. Secondly, the overall coupling model is constructed according to coupling parameters, like tension force, which join together distributed subsystems. Finally, the overall model is simplified according to time-scale principle which can retain main eigenvalues values and significant state variables, and a practical model is obtained. This modeling method has universal reference and application value to coupling modeling of the complicated electro-mechanical systems whose subsystems are coupled by workpiece. The coupling model can be applied to synthetic studies on complicated electromechanical systems, such as chatter analysis, parameter optimization, optimum control.

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