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Decoupling control of tension based on pole assignment for temper mill

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Abstract: Analyze the problem existing in the product quality of temper mill and propose a decoupling control strategy based on pole assignment. The theoretic analysis, computer simulation and industrial experiment prove that the strategy can implement decoupling control among the forward tension, the backward tension and the roller speed of temper mill, lower their coupling degree, improve control performance and ultimately help promote product quality.

Key words: pole assignment; temper mill; tension; decoupling control

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基于极点配置的平整机张力解耦控制

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摘要: 分析了平整机产品质量存在的问题;提出了基于极点配置的解耦控制策略. 理论分析、计算机仿真和工业实验都表明该控制方法能实现对平整机前张力、后张力和工作辊速度的解耦控制,降低了它们之间的相互耦合程度,改善了系统的控制效果,有利于提高带材产品的质量.

关键词: 极点配置; 平整机; 张力; 解耦控制

1 Introduction

Temper mill is one of significant facilities which produce sheet-strip steel such as car sheet, tin-plating sheet, color sheet and so on. The key to guaranteeing sheet-strip steel product quality of temper mill is to strictly keep the forward tension and the backward tension acting on workpiece and the roller speed constant. Otherwise the light and shade streaks will appear on the surface of strip steel. Because of the failure to ensure the product quality concerned, about 20,000 tons strip steel is prohibited from leaving the large-scale steel factories in China each year. Through testing and investigating CM04 temper mill of Cold Rolling Factory, Baoshan Steel Group, it is discovered that the tension is indirectly controlled by keeping armature current in electric motors of winding reel and pay-off reel when temper mill works normally, and roller speed is regulated by the 2-closed-loop tuning speed system[1,2]. But the winding reel subsystem, the stand subsystem and the pay-off reel subsystem are designed individually, so that the coupling relation among the three subsystems is not involved considered at all when the strip steel joins them together. In fact, the forward tension, the backward tension and the roller speed are mutually coupled and affected[3,4]. Sometimes the forward tension and the backward tension vibrate intensely as a result of coupling action, and bring about inferior or useless products (see also Fig. 1).

Beginning with rolling model of tension-speed control system, the paper will explore an output-feedback decoupling controller based on pole assignment to remove the coupling relations among the forward tension, the backward tension and the roller speed, then to tune the 3 controlled parameters according to their technological requirement[5].

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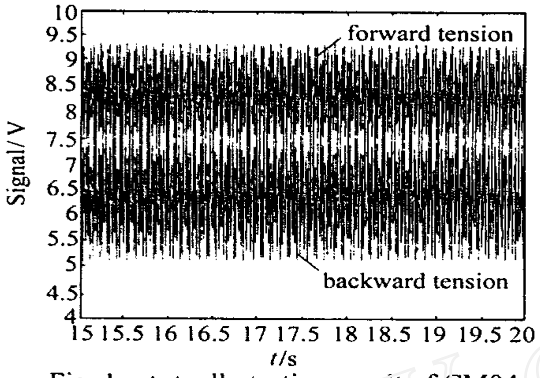

Fig. 1 Actually testing result of CM04

2 Physical and mathematical models of tension-speed system

2.1 Physical model

The simplified rolling model of temper mill is shown as Fig. 2. It consists of the winding reel subsystem, the stand subsystem and the pay-off reel subsystem. When temper mill works normally, the strip steel joins the 3 subsystems together into a complicated electromechanical coupling system.

The notations and parameters in Fig. 2 are explained as follows:

p —mark below parameter, indicates the parameter belonging to pay-off reel subsystem;

s —mark below parameter, indicates the parameter belonging to stand subsystem;

w —mark below parameter, indicates the parameter belonging to winding reel subsystem;

u_p, u_s, u_w —armature voltage, V;

L_p, L_s, L_w —armature inductance, H;

R_p, R_s, R_w —armatures resistance, Ω;

v_p, v_w —line speed of reel, m/min;

v_i —entry speed of strip steel, m/min;

v_o —exit speed of strip steel, m/min;

t_f —forward tension, N;

t_b —backward tension, N.

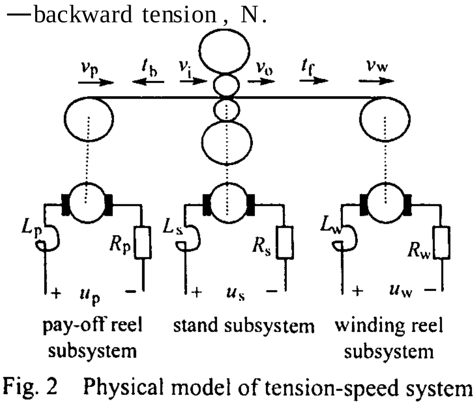

Fig. 2 Physical model of tension-speed system

Note that the drive ratios are all equal to 1 in the whole system.

2.2 Mathematical model

Referring to physical model, according to the balance principle of armature voltage and dynamics and defining the armature current and the rotatory speed of motor as independent state variables, the voltage and dynamic balance equations of the 3 subsystems can be written as expressions (1), (2) and (3).

$$\begin{cases} L_p \dfrac{d i_p}{d t} + R_p i_p + K_{ep} n_p = u_p, \\ \dfrac{GD_p^2}{375}\dfrac{d n_p}{d t} + f_p n_p - r_p t_b = K_{mp} i_p, \end{cases} \tag{1}$$

$$\begin{cases} L_s \dfrac{d i_s}{d t} + R_s i_s + K_{es} n_s = u_s, \\ \dfrac{GD_s^2}{375}\dfrac{d n_s}{d t} + f_s n_s + r_s t_b - r_s t_f = K_{ms} i_s, \end{cases} \tag{2}$$

$$\begin{cases} L_w \dfrac{d i_w}{d t} + R_w i_w + K_{ew} n_w = u_w, \\ \dfrac{GD_w^2}{375}\dfrac{d n_w}{d t} + f_w n_w + r_w t_f = K_{mw} i_w, \end{cases} \tag{3}$$

where

i_p, i_s, i_w —armature current, A;

n_p, n_s, n_w —rotatory speed of motor, r/min;

GD_p^2, GD_s^2, GD_w^2 —total rotatory inertia in axis of motor, N·m^2;

f_p, f_s, f_w —friction coefficient, N·min/r;

r_p, r_s, r_w —radius of reel or roller, m;

K_{ep}, K_{es}, K_{ew} —electric potential coefficient, V·min/r;

K_{mp}, K_{ms}, K_{mw} —torque coefficient of motor, N·m/A.

Here, the marks below parameters p, s and w are explained as above.

According to rolling theory, if there exists speed difference in length direction of rolled workpiece to result in relative displacement of different-position metal, tension happens in rolled workpiece. Thus, the deviations of the forward tension and the backward tension of the rolled strip steel in temper mill can be expressed as Eq. (4):

$$\begin{cases} \dfrac{d t_f}{d t} = \dfrac{A_f E}{L_f}(v_w - v_o), \\ \dfrac{d t_b}{d t} = \dfrac{A_b E}{L_b}(v_i - v_p), \end{cases} \tag{4}$$

where

A_b —the crosscut area of input steel strip, m^2;

A_f —the crosscut area of output steel strip, m^2;

L_b —the length of steel strip between the pay-off reel and stand, m;

L_f —the length of steel strip between the stand and the winding reel, m;

E —elastic modulus of steel strip, N/ m^2.

Let the independent state variables n_p, n_s and n_w subtitute for v_p, v_o, v_i and v_w, the Eq. (4) can be rewritten as follows:

$$\begin{cases} \dfrac{dt_f}{dt} = \dfrac{A_f E r_j}{L_f} n_w - \dfrac{A_f E r_s(1+S_f)}{L_f} n_s, \\ \dfrac{dt_b}{dt} = \dfrac{A_b E r_s(1-S_b)}{L_b} n_s - \dfrac{A_b E r_p}{L_b} n_p, \end{cases} \tag{5}$$

where

S_f —the forward sliding coefficient of rolled steel strip in the stand;

S_b —the backward sliding coefficient.

To sum up the above statement, the expressions (1), (2), (3) and (5) have 8 equations and 8 independent state variables. They describe quantitatively the dynamic and static performance of the tension-speed system of temper mill. They are just the mathematical model that should be constructed. It is known from the model that the forward tension t_f and the backward tension t_b penetrate through the 3 subsystems and join them together to form a complicated electromechanical coupling system. Especially, expressions (2) and (5) indicate clearly that t_f, t_b and the roller speed n_s are directly coupled. If their coupling influences are neglected and settled individually respectively, the poor control effect will arise.

3 Decoupling control strategy

The tension-speed system may be approximately regarded as 3-input and 3-output multivariable and minimum-phase linear system, Let

$$U(k) = [u_s(k) \quad u_w(k) \quad u_p(k)]^T,$$

$$Y(k) = [n_s(k) \quad t_f(k) \quad t_b(k)]^T,$$

and discretify the mathematical model discussed above, the ARMA model of the controlled plant is shown as follows:

$$A(z^{-1})Y(k) = B(z^{-1})U(k). \tag{6}$$

Thus, the transfer function is

$$G(z^{-1}) = A^{-1}(z^{-1})B(z^{-1}), \tag{7}$$

where $A(z^{-1})$ and $B(z^{-1})$ are polynomial matrix ascertained by structural parameters of system. They are described as follows:

$$\begin{cases} A(z^{-1}) = 1 + A_1 z^{-1} + A_2 z^{-2} + \cdots + A_n z^{-n}, \\ B(z^{-1}) = B_1 z^{-1} + B_2 z^{-2} + \cdots + B_m z^{-m}, \end{cases} \tag{8}$$

where $A_1, A_2, \cdots, A_n$ and $B_1, B_2, \cdots, B_m$ are real constant matrix, and $m \le n$.

The design target of decoupling control strategy is to select practicable output feedback matrix $F(z^{-1})$ and prepositional compensation matrix $P(z^{-1})$ shown as Fig. 3 to make closed-loop transfer function $T(z^{-1})$ be a diagonal matrix or a diagonal-dominant matrixex, then design single-loop control matrix $C(z^{-1})$, i. e., $C(z^{-1})$ is also diagonal.

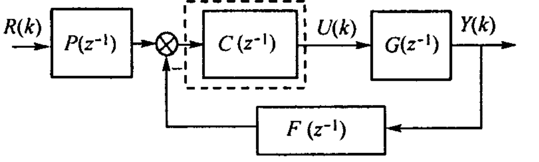

Fig. 3 The structural block diagram of the decoupling control system

It is known from Fig. 3 that if $C(z^{-1})$ is temporarily neglected, the decoupling control law $U(k)$ may be expressed as follows:

$$U(k) = P(z^{-1})R(k) - F(z^{-1})Y(k), \tag{9}$$

where

$$\begin{cases} F(z^{-1}) = F_0 + F_1 z^{-1} + F_2 z^{-2} + \cdots + F_{n_f} z^{-n_f}, \\ P(z^{-1}) = P_0 + P_1 z^{-1} + P_2 z^{-2} + \cdots + P_{n_p} z^{-n_p}, \end{cases} \tag{10}$$

where $F_0, F_1, \cdots, f_{n_f}, P_0, P_1, \cdots, P_{n_p}$ are real constant matrixes, $R(k) = [r_1(k) \quad r_2(k) \quad r_3(k)]^T$ is reference input vector.

Put expression (9) into expression (6), the closed-loop transfer function $T(z^{-1})$ of the control system is shown as follows:

$$T(z^{-1}) = [A(z^{-1}) + B(z^{-1})F(z^{-1})]^{-1}B(z^{-1})P(z^{-1}). \tag{11}$$

Assume that, after pole assignment, the expected closed-loop transfer function $T_e(z^{-1})$ is described as follows:

$$T_e(z^{-1}) = A_e^{-1}(z^{-1})B_e(z^{-1}), \tag{12}$$

where

$$\begin{cases} A_e(z^{-1}) = I + A_{e1}z^{-1} + A_{e2}z^{-2} + \cdots + A_{en}z^{-n_e}, \\ B_e(z^{-1}) = B_{e1}z^{-1} + B_{e2}z^{-2} + \cdots + B_{em}z^{-m_e}, \end{cases} \tag{13}$$

and $A_{e1}, A_{e2}, \cdots, A_{en}, B_{e1}, B_{e2}, \cdots, B_{en}$ are real constant diagonal matrix.

If the stable and practicable $P(z^{-1})$ and $F(z^{-1})$ can be designed, and make the equation $T(z^{-1}) = T_e(z^{-1})$ be tenable, the control system shown by Fig. 3 is thoroughly decoupled. Thus, let the following equations be tenable:

$$\begin{cases} A_e(z^{-1}) = A(z^{-1}) + B(z^{-1})F(z^{-1}), \\ B_e(z^{-1}) = B(z^{-1})P(z^{-1}). \end{cases} \tag{14}$$

So, $P(z^{-1})$ and $F(z^{-1})$ can be ascertained by expression (14). However, it is very difficult to find limited-order solutions of $P(z^{-1})$ and $F(z^{-1})$ from expression (14) as a result of involving polynomial division operation. Therefore, a stable filter $1/f(z^{-1})$ needs to be introduced to $C(z^{-1})$. Now, $U(k)$ is expressed as follows:

$$U(k) = [P(z^{-1})R(k) - F(z^{-1})Y(k)]/f(z^{-1}), \tag{15}$$

where, $f(z^{-1}) = f_0 + f_1z^{-1} + f_2z^{-2} + \cdots$ and $f_0 \neq 0$. If $B(z^{-1})$ is nonsingular matrix, $F(z^{-1})$ and $P(z^{-1})$ may be expressed as follows:

$$\begin{cases} F(z^{-1}) = B^{-1}(z^{-1})[A_e(z^{-1}) - A(z^{-1})]f(z^{-1}), \\ P(z^{-1}) = B^{-1}(z^{-1})B_e(z^{-1})f(z^{-1}). \end{cases} \tag{16}$$

In which, $B^{-1}(z^{-1})$ can be expressed as follows:

$$B^{-1}(z^{-1}) = \mathrm{adj}(B(z^{-1}))/\det(B(z^{-1})) = \mathrm{adj}(B(z^{-1}))/[z^{-d}(b_0 + b_1z^{-1} + b_2z^{-2} + \cdots)], \tag{17}$$

where $b_0 \neq 0$. It is known from the expression (16) and (17) that, if let $f(z^{-1}) = b_0 + b_1z^{-1} + b_2z^{-2} + \cdots$, the final expressions of $P(z^{-1})$ and $F(z^{-1})$ are:

$$\begin{cases} F(z^{-1}) = z^d[\mathrm{adj}\ B(z^{-1})][A_e(z^{-1}) - A(z^{-1})], \\ P(z^{-1}) = z^d[\mathrm{adj}\ B(z^{-1})]B_e(z^{-1}). \end{cases} \tag{18}$$

Obviously, $P(z^{-1})$ and $F(z^{-1})$ are limited-order polynomial. They can decouple the control system shown by Fig. 3, and the poles of the system can be assigned in expected position.

4 Simulation and industrial experiment

4.1 Computer simulation

Let real values substitute the parameters in the mathematical model, ascertain sample period T = 0.02 s, discretify the model by calling function c2d() in Matlab, then simplify the discreted model with Padé method, so $A(z^{-1})$ and $B(z^{-1})$ in the model expression (6) of the controlled plant are ascertained.

The expected poles of closed-loop system should be assigned as close as possible to the point (0,0) of Z-plane so that the control system has better performance. In addition, when the reference inputs vary from 0 to 10 V, the roller speed and the tensions vary correspondingly from 0 to 984 r/min and from 0 to 100 kN, $A_e(z^{-1})$ and $B_e(z^{-1})$ in the expression (12) are ascertained as follows:

$$A_e(z^{-1}) = \begin{bmatrix} 1-0.1z^{-1} & 0 & 0 \\ 0 & 1-0.2z^{-1} & 0 \\ 0 & 0 & 1-0.3z^{-1} \end{bmatrix},$$

$$B_e(z^{-1}) = \begin{bmatrix} 0.9z^{-1} & 0 & 0 \\ 0 & 0.8z^{-1} & 0 \\ 0 & 0 & 0.7z^{-1} \end{bmatrix}.$$

On the basis of the expressions (17) and (18), $f(z^{-1})$, $F(z^{-1})$ and $P(z^{-1})$ can be ascertained.

Assume the reference input $r_1(k) = 5.93$ V, $r_2(k) = 8.44$ V and $r_3(k) = 6.35$ V, i.e., the set values of the roller speed, the forward tension and the backward tension are respectively equal to 584 r/min, 84.4 kN and 63.5 kN. Let sample period T = 0.02 s, the result is drawn in Fig. 4 after the closed-loop system shown in Fig. 3 runs 5 s.

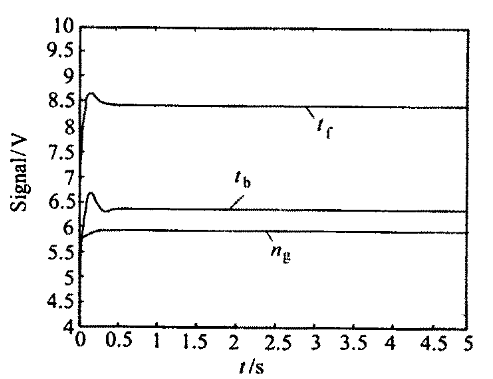

Fig. 4 Simulating result

It is known from Fig. 4 that the 3 controlled parameters trace precisely their own goals after less than 1 second, the quickness and static error meet the technological requirement, and the coupling relations among the 3 parameters are removed thoroughly.

4.2 Industrial experiment

In order to make a comparison with the coupling control effect Fig. 1, the same operating mode is adopted in the decoupling control experiment. Here, the rolled strip material is carbon steel, the width of the strip steel is 1000 mm, the gauge of strip steel is 1mm, the diameter of the stand roller is 625 mm, the surface crudeness of the stand roller is 80 μ-inch, and the flow ratio of lubricant is 80 %.

The set values of the roller speed, the forward tension and the backward tension are respectively 584 r/min, 84.4 kN and 63.5 kN. Their corresponding reference inputs are respectively 5.93 V, 8.44 V and 6.35 V. After the erection of the initial tension, the output signals $U(k)$ of the decoupling controller are respectively sent to the reference input terminals of the speed regulator (PI) of the stand subsystem, the current regulator (PI) of the winding reel subsystem and the current regulator (PI) of the pay - off reel subsystem. After the system is started, the testing result is drawn as shown in Fig. 5.

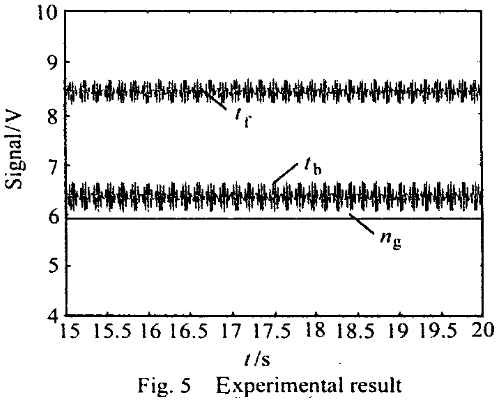

Fig. 5 Experimental result

Compared with Fig. 1, the vibrating amplitude of the tension is weakened, the coupling degree is lowered, and the control effect is obviously improved. However, compared with the simulating result Fig. 4, the coupling influence among the controlled parameter still exists, and the coupling vibration is not thoroughly removed. Thefundamental causes lie in the precision of the model, the some uncertainties of the actual plant, the rounding error of the controller design, and so on.

5 Conclusions

The decoupling controller designed through the outputs of the plant can weaken or remove the coupling relations among the 3 subsystems, and assign the poles of closed-loop systems in the desired positions so that the control system has better the dynamic and static performances. The theoretic analysis, the computer simulation and the industrial experiment have proved that the decoupling control strategy can implement decoupling control of the forward tension, the backward tension and the roller speed of temper mill and lower their coupling degree, improve control performance so that the quality of the strip steel will be promoted.

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