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The research of speed setting model and speed control of the tandem skew rolling mill

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Abstract. The Tandem Skew Rolling (TSR) mill is a new metal forming machine for producing seamless steel tubes.Since the billet is pierced and rolled in two sets of rolls in the TSR mill,the speed coordination control of the TSR mill is crucial in improving the quality of products during the rolling process.According to the principle of metal mass flow equation,the study present is designed to establish the speed setting model and the relations of the tandem rolling speed for the piercing roll and the rolling roll.Because the rolling speed could be easily affected by the material,the temperature,the mechanical properties and the tension,the control performance of the traditional PID controller is not ideal.Dynamic matrix control (DMC) is an advanced control strategy based on model predictive control technique.In this paper,DMC algorithm is designed to control the rolling speed and improve the dynamic performances of the TSR mill.The results of simulation and experiments showed the excellent performance of the proposed DMC algorithm.

Key words. Tandem skew rolling mill,speed system,steady state rolling,dynamic matrix control.

1. Introduction

The Tandem Skew Rolling (TSR) process is a new method for producing seamless steel tubes,in which the billet is continuously pierced and rolled[1].The Tandem Skew Rolling (TSR) mill consists of two things:piercing section and rolling section.In the rolling process,the billet which is heated in the rst place is pierced in the piercing section,and then the pierced billet is sent to the rolling section.These two sections work simultaneously on the same piece of billet,so the tandem rolling relation is formed during the working process.The dynamic performance of the rolling speed is one

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of the important indicators to measure the dynamic stability of control system.In the rolling process,the rolling speed will be affected by the material,the temperature,mechanical properties,tension et al.If the speed of the roll is unmatched in the piercing section and the rolling section,the tube may be piled or stretched. As a result,the tube produced cannot reach the qualification.For the TSR mill,we hope that the speed control precision is higher,and the response speed is faster.All this time,many scholars turned to the study and practice of rolling process control.The intelligent algorithm is proposed to control the speed of DC motor,which can obtain the adaptive control of rolling speed,such as the wavelet neural network,the Particle Swarm Optimization[2,3].In order to control the change of rolling force in a better way,fuzzy control and neural network intelligent optimization method are applied to rolling force prediction[4,5].

Predictive control is an advanced method of process control based on the model.The main characteristic of predictive control is the use of the model of the system for the prediction of the future behavior of the controlled variables.One advantage of predictive control is that concepts are very simple and intuitive,the robustness and the anti-interference is strong.In a word,complex constrained optimization control problem can be solved with predictive control[6].The distributed predictive control is applied in the cooling system of the steel rolling enterprise[7].In this paper,the separate transmission ways are used by the main driving system of the tandem skew rolling mill[8].On the other hand, three rolls of the piercing section are driven by three AC motors.On the other hand,three rolls of the rolling section are driven by three DC motors.In this paper,with the consideration of the characteristics of the tandem skew rolling process,the precise speed setting model and the speed equation of the tandem rolling are established in the paper according to the characteristics.Then, predictive control has the ability to anticipate future events and can take control actions accordingly. Dynamic matrix control algorithm is proposed to control roll speed of the rolling section.The experiment proved that the algorithm can guarantee the accuracy and the quickness of the roll speed. The method provides a good foundation for improving the quality of the products.

2. The speed setting model of main drive system

In the tandem skew rolling process,when the tube enters the rolling section after it is pierced.In the TSR process,when the tube enters the rolling section after it is pierced, DC motor speed decreases in account with load change.If the speed can't recover in a short time,the speed mismatching may be caused between the piercing section and rolling section,which lead to heap steel and moreover affect the quality of steel pipe.

In order to ensure the workpiece rolled smoothly between the two groups of rolls,neither heaped,nor stretched,the rolling process is controlled to follow mill metal flow equation.But in practical production,the roller's speeds are unmatched in the piercing section and the rolling section due to various reasons.For this reason,the speed controlling and matching are needed to be studied.

In order to ensure the tensile strength,yield strength of steel tube,it must be ensured that the nishing temperature is basically stable.When the billet is rolled in the TSR mill,the form of the heat transfer is quite complex,in which heat dissipation is caused by radiation,convection,conduction,and meanwhile heat increase is caused by contact friction and plastic deformation.The TSR mill can be divided into three portions in Fig.1.The thermometers T_1,T_2 are equipped at the two ends of the rolling mill.

In the rst portions,the heat loss is mainly caused by the heat radiation in the process of transporting. Because the transport distance of the TSR mill is shorter,the radiation temperature can be calculated by the following formula

$$\Delta t = -\frac{\varepsilon\sigma}{c_p\gamma r}\left(\frac{t+273}{100}\right)^4 \Delta\tau \tag{1}$$

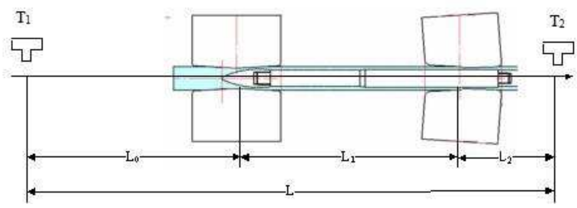

Fig. 1. The structure of the TSR mill. The thermometers T_1, $T_2$are equipped at the two ends of the rolling mill.

When the tube billet is entering into the TSR mill,the plastic deformation heat and the conduction heat loss generated by the friction between the steel pipe and the roller can offset each other.Meanwhile the radiation cooling and the water cooling between the frames are considered to be an equivalent of the cooling system.The temperature drop formula of the TSR mill for each portion is:

$$In\frac{t_i - t_W}{t_{i-1} - t_W} = -K_F\frac{L_i}{h_i v_i} \tag{2}$$

Where t_i is the steel tube temperature in i section. t_{i-1} is the steel tube temperature in i-1 section. t_W is the temperature of the cooling water. K_F is cooling capacity coefficient. h_i is the thickness of steel pipe in i section. v_i is the speed of steel pipe in i section. L_i is the distance from section to i-1 section. In the process of rolling,the metal mass flow equation is written as follows

$$F_i v_i = F_2 v_2 \tag{3}$$

Where $v_2$the outlet velocity of the tube in the rolling section. F_i is the sectional area of the tube in i section. F_2 is the export sectional area in the rolling section. Hence the temperature drop formula is rewritten as follows

$$In\frac{t_i - t_W}{t_{i-1} - t_W} = -K_F\frac{L_i F_i}{h_i F_2 v_2} \tag{4}$$

The temperature drop in two portions together is added to get the temperature drop formula of the whole frame

$$In\frac{t_{Fo}-t_W}{t_{Fe}-t_W}=-K_F\frac{1}{F_2v_2}\sum_{i=0}^{2}\frac{L_iF_i}{h_i} \tag{5}$$

Where $t_{Fo}$the temperature of the tube in the exit of the rolling is section. t_{Fe} is the temperature of the tube in the entrance of the piercing section which is calculated by the formula (1).Thus,to assume the outlet temperature of rolling section,the outlet velocity of rolling section is calculated based on equation (5)

$$v_2=\frac{-K_F\sum_{i=0}^{2}\frac{L_iF_i}{h_i}}{F_2In\left(\frac{T_{Fo}-T_W}{T_{Fe}-T_W}\right)} \tag{6}$$

The skew rolling is used in the tandem skew rolling process.On the basis of the kinematics theory of skew rolling, the speed of the roller in the rolling section is

$$n_{r2}=\frac{60v_2}{\eta_2\pi D_2\sin\alpha_2\cos\beta_2} \tag{7}$$

Where $\alpha_2,\beta_2$are feed angle and entrance face angle in the rolling section respectively, η_2 is the axial sliding coefficient of the shell, D_2 is the roller's diameter of the exit.On the basis of the formula (6) and (7),the speed of the roller in the rolling section is set as follows

$$n_{r2}=\frac{60}{\eta_2\pi D_2\sin\alpha_2\cos\beta_2}\times\frac{-K_F\sum_{i=0}^{2}\frac{L_iF_i}{h_i}}{F_2In\left(\frac{T_{Fo}-T_W}{T_{Fe}-T_W}\right)} \tag{8}$$

In the rolling process,the billet is pierced,and then the pierced shell is rolled between the piercing section and the rolling section.The relation of continuous rolling is formed.The metal mass ?ow equation is written as follows

$$F_1v_1=F_2v_2 \tag{9}$$

Where v_1 is the outlet velocity in the piercing section, F_1 is the exit area of the piercing section, The relation of $v_1$and $n_{r1}$is as below

$$n_{r1}=\frac{60v_1}{\eta_1\pi D_1\sin\alpha_1\cos\beta_1} \tag{10}$$

where $n_{r1}$is the roll speed of the piercing section.$\alpha_1,\beta_1$are the feed angle and the entrance face angle in the piercing section respectively.η_1 is the axial sliding coefficient of the piercing section. D_1 is the roller's diameter of the exit area in the piercing section.The roller's speed of the piercing section is set as follows

$$n_{r1} = \frac{F_2}{F_1} \times \frac{60}{\eta_1 \pi D_1 \sin\alpha_1 \cos\beta_1} \times \frac{-K_F \sum_{i=0}^{2} \frac{L_i F_i}{h_i}}{F_2 In\left(\frac{T_{Fo}-T_W}{T_{Fe}-T_W}\right)} \tag{11}$$

The speed ratio of the piercing section and the rolling section is

$$\frac{n_{r1}}{n_{r2}} = \frac{\eta_2 F_2 D_2 \sin\alpha_2 \cos\beta_2}{\eta_1 F_1 D_1 \sin\alpha_1 \cos\beta_1} \tag{12}$$

During rolling process,especially the continuous rolling, the process can only proceed smoothly when the speed ratio of the piercing section and the rolling section is satised by the equation (12).Usually, the slip is inevitably produced between the rolled piece and the roller when the pipe is rolled.The axial sliding coefficient is affected by the rolling velocity,temperature,and plug advance.Here,the empirical formula is used.

3. The design of the Predictive Controller

Predictive control,which is aimed at optimizing control problem,has achieved great success since being used to solve complex problem of constrained optimization control in complex industrial process[6].In the TSR process,the speeds of the rolls in piercing and rolling section are easily affected by the external environment,such as metal deformation resistance,material temperature,tension etc.. Due to those problems,the parameters setting of PID controller is more difficult.In this paper,we use the predictive control algorithm as a controller,which can predict the next hour speed values.The algorithm maintains the good dynamic performance of the control system through adjusting the control efforts of the future.

Dynamic matrix control (DMC) is a kind of important predictive control algorithm,in which the system dynamic model is described by the step response characteristics of the controlled object.The control structure of the DMC algorithm is mainly made up of prediction model,receding horizon optimization and revising feedback.The roller's speed is controlled by the output of receding horizon optimization.It is assumed that y is the process output,u is the process input,y_r is target velocity,y_m is the output of prediction model,y_p is the output of revising feedback,and e is the error of y_m and y.

DMC algorithm is an algorithm which use certain control strategy by optimization.Supposing a_i $i = 1, 2, ...N$ is the step response coefficients of the controlled object,where N is the model horizon, the predictive output of the process at time k can be described by the following model

$$y_m\left(k+i\left|k\right.\right) = y_0\left(k+i\left|k\right.\right) + a_i \Delta u\left(k\right), i = 1, 2, ..., N \tag{13}$$

Where $y_0\left(k+i\left|k\right.\right)$ $(i = 1, 2, ...N)$ is the initial value of the future output at k time when $\Delta u\left(k\right)$ is assumed unchanged.

In the same way,under the effect of M continuous control increment $\Delta u\left(k\right),...\Delta u\left(k+M-1\right)$, the output value of the future time is written by matrix form as follows

$$Y_m\left(k\right)=Y_0\left(k\right)+A\Delta U\left(k\right) \tag{14}$$

Where $Y_m\left(k\right)=\left[y_m\left(k+1\left|k\right.\right)\quad y_m\left(k+2\left|k\right.\right)\ ...\ y_m\left(k+N\left|k\right.\right)\right]^T$is the predictive value.$Y_0\left(k\right)=\left[y_0\left(k+1\left|k\right.\right)\quad y_0\left(k+2\left|k\right.\right)\ ...\ y_0\left(k+N\left|k\right.\right)\right]^T$ is the initial value.$\Delta U\left(k\right)=\left[\Delta u\left(k\right)\quad \Delta u\left(k+1\right)\ ...\ \Delta u\left(k+N-1\right)\right]^T$ is the control increment.A is dynamic matrix coefficient and described by

$$A=\begin{bmatrix} a_1 & & & 0 \\ a_2 & a_1 & & \\ ... & & & \\ a_n & a_{n-1} & ... & a_{n-m+1} \end{bmatrix} \tag{15}$$

M is the control horizon.$k+i\left|k\right.$ is the prediction at time $k+i$.The error is produced between the predicted value and the actual output value when there is random disturbance,modeling deviation.So revising feedback is adopted to correct the predicted value online.The error is written by

$$e\left(k+1\right)=y\left(k+1\right)-y_m\left(k+1\left|k\right.\right) \tag{16}$$

In order to eliminate the error of predicted value,$e(k+1)$is corrected by the weighted as follows

$$Y_p=Y_m+He(k+1) \tag{17}$$

Where $Y_p=\left[y\left(k+1\right),y\left(k+2\right),...,y\left(k+p\right)\right]^T$is the predictive value after correction.$H=\left[h_1,h_2,...,h_N\right]^T$is correction vector.

Receding horizon optimization is used to determine the control action in the future by some performance index.The future behavior of the system in performance index is determined by the control strategy based on the prediction model.The optimal control law written at time k is as follows

$$\min J\left(k\right)=\sum_{i=1}^{P}q_i[y_r(k+i)-y_p(k+i\left|k\right.)]^2+\sum_{j=1}^{M}r_j\Delta u^2(k+j-1) \tag{18}$$

Where q_i is the weight of the output prediction error;r_j is the weight matrix of the control volume. Suppose $\frac{\partial J(k)}{\partial\Delta u(k)}=0$,then the control increment can be expressed as

$$\Delta U(k)=(A^TQA+R)^{-1}A^TQ[Y_r(k)-Y_p(k)] \tag{19}$$

In the DMC algorithm,the actual control value $u\left(k\right)=u\left(k-1\right)+\Delta u\left(k\right)$ acts on the controlled plant.

4. The experiment results

In this paper,the rollers in the piercing section are driven by AC motor and the rollers in the rolling section are driven by DC motor.Because DC motor has some advantages such as wide range of speed regulation,good performance and simple circuit,the DC motor speed of the rolling section is considered to be controlled.The roller's speed of the rolling section is calculated by the formula (7).

$$n_{r2} = n_{r1} \frac{\eta_1 F_1 D_1 \sin\alpha_1 \cos\beta_1}{\eta_2 F_2 D_2 \sin\alpha_2 \cos\beta_2} \tag{20}$$

According to the characteristics of the tandem skew rolling mill, the design parameters are listed in Table 1.

The thickness of the pierced tube is 5mm.The thickness of the rolled tube is 4.5mm.The axial sliding coefficient of the piercing section is 0.87.The axial sliding coefficient of the rolling section is 0.8. According to Table 1,the roll speed of the rolling section is 174rpm.The ratio of the planetary gear reducer installed between the roll and the motor is 5.The set speed of the DC motor in the rolling section is 870rpm by the formula (15).The type of DC motor is Z4-160-31.Rated power is 22kw.Rated speed is 1000rpm.Rated voltage is 400V.Rated current is 64.8A.

Table 1 The TSR process parameters

	parameter	value
Piercing section	Feed angle()	7
	Entrance face angle()	0
	Roll diameter(mm)	180
	Roll speed(rpm)	165
Rolling section	Feed angle()	8
	Entrance face angle()	4
	Roll diameter(mm)	180
Mandrel diameter(mm)		30
Billet diameter(mm)		40

The equivalent circuit parameters of the DC motor used in the experiment are $R = 0.675\Omega, L_A = 15.2mH, GD^2 = 0.88kg \bullet m^2$.The transfer function model of the DC motor is written as follows

$$W(s) = \frac{1/C_e}{T_m T_l s^2 + T_m s + 1} = \frac{9394.61}{s^2 + 43.47s + 3344.48}$$

Fig.2 shows the simulation models of DMC controller by Matlab/Simulink. Fig.3 shows the speed response curve of the ordinary PID controller and DMC controller. The parameters of the ordinary PID controller are adjusted by Ziegler-

Nichols method.

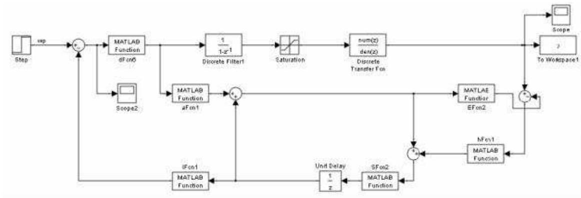

Fig. 2. The simulation models of DMC controller by simulink, the sampling time is 0.001

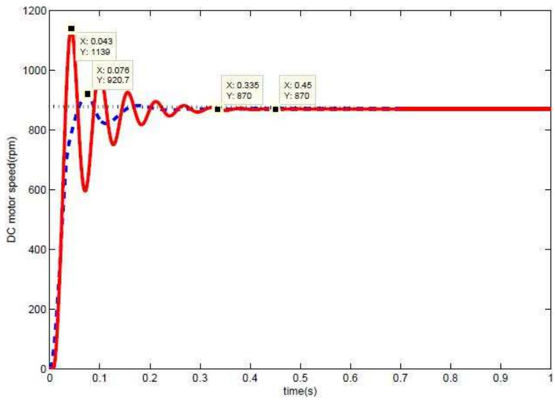

Fig. 3. The speed response curve

Compared with the traditional PID controller in Table 2,DMC controller has advantages of small overshoot,short settling time and smooth transitional process.It is feasible that DMC algorithm is adopted to improve the dynamic performance of the tandem skew rolling mill.

Table 2 The simulation results of the speed response

Type	Steady state error	Overshoot(%)	settling time(s)
PID controller	0.5	0.31	0.45
DMC controller	0.0	0.06	0.33

Fig.4 shows the speed curve controlled the ordinary PID controller and DMC controller in rolling process respectively.It is notable that the DC motor speed is 870rpm at 1.2s, and 0.86s later, the tube is bitted by the rollers of the rolling section.The DC motor speed is decreased as a result of load change in Fig.4(a).Then the DC motor speed increases to 871rpm at 3.3s.In the whole rolling stage, the DC motor speed is inconsistent with the set point. Fig.4(b) shows the speed curve controlled the DMC controller in rolling process.Compared with Fig.4(a),the speed response of the DC motor is fast, and the speed can quickly achieve the set point when the load changes.

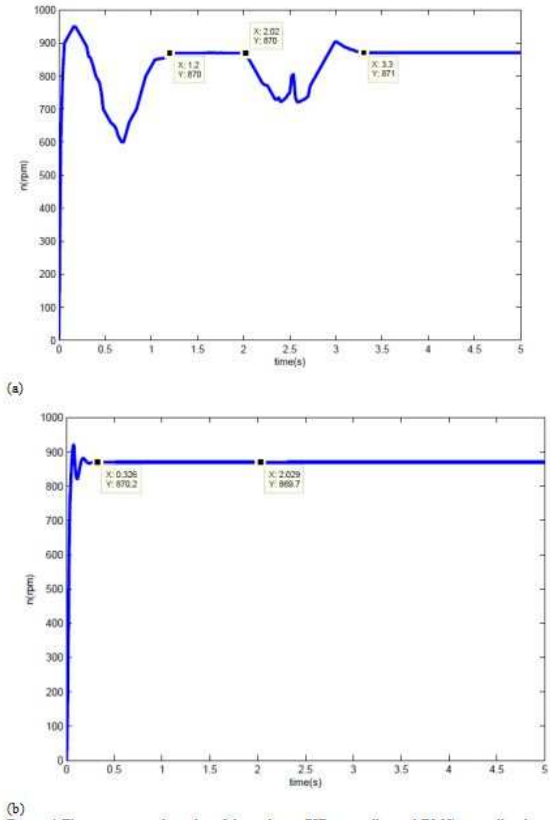

Fig. 4. The experimental results of the ordinary PID controller and DMC controller,the sampling time is 0.001

5. Conclusion

This paper focuses on the process characteristics of the tandem skew rolling mill.Firstly,the setting model of the roll velocity in the piercing section and the rolling section is proposed based on the principle of metal mass ?ow equation.Secondly,since it is important that the rolling speed is stable in rolling process.While the roll speed will be affected by the external factors such as the grid quality, pipe material etc.,the DMC algorithm is used to substitute PID controller considering its successful applications in various practical problems.The simulation results show that the control performance of the DMC algorithm is superior to PID controller.Finally the experiment results show that the response speed and the stability of the mill are improved by the DMC algorithm.

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