Modeling and Gain Scheduling Adaptive Control of Tension Control System for Continuous Annealing Process

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Abstract—In continuous annealing process, strip tension is an important factor that decides whether the continuous annealing line could work steadily and promptly or not. However, the tension fluctuations are inevitable as the continuous annealing process requires accelerating and decelerating frequently. In this situation, the synchronous response of the roll-speed helps to reduce this type of tension fluctuations. So here, based on the developed object model close to the actual process, a new adaptive control method with two compensations, feedforward compensation and gain scheduling adaptive compensation has been proposed to compensate the axletree friction and the strip inertia’s influences to the tension control respectively. The simulation and application results show that this method is helpful to restrain the tension fluctuations caused by the mismatch of the adjacent roll speed, and is beneficial to the stability of tension control.

I. INTRODUCTION

CONTINUOUS annealing line is the key part for producing high-quality cold-rolling strip product, in which the strip is recrystallized and annealed to improve the microstructure, the plastic and metal forming characteristic. During the continuous annealing process, the strip tension being between the appropriate bound is essential to the line’s high-speed and stable running, which will be helpful to prevent strip position deviation, hot bending, eventually to get well-shaped product. However, it is inevitable for the strip tension to fluctuate in case the speeds of the neighboring two rolls are not synchronous when the strip speeds up or slows down in the furnace. And because the strip is rigid, small deviation of the speed will cause large tension fluctuation. This fluctuation will not only affect the product quality, it could also make serious accidents such as strip broken and etc. Therefore, to decrease the tension fluctuation, it is necessary to make all of the rolls regulate the speeds synchronously when the line accelerates or decelerates.

To get the satisfying performance of the tension control system, based on the characteristics analysis of complex tension object (the axletree friction which is nonlinear relational with the roll-speed, the strip inertia’s influence and etc), a adaptive control method with the friction torque feedforward compensation and strip inertia gain scheduling compensation is proposed, with the following three contents: First, compensate the friction torque which is non-linear relative to the speed by gain scheduling feedforward controller; Second, adjust the ratio coefficient of the convertor ASR to benefit rolls speed response synchronization when producing different strip (particularly for the larger cross-sectional area ones); Third, to make the bridle rolls’ loads balanced, a new control objective index is defined and the corresponding control scheme is designed.

II. FURNACE ZONE TENSION SYSTEM DESCRIPTION

A. Process Description

To make the tension stable throughout the whole line, one continuous annealing process line sets up a total of N tension sensors(TM1~TMN) to carry out closed-loop tension control. As shown in Fig. 1, here we study the section between TM11 ~ TM12, with a total of 24 rolls, which are driven by separate convertors and motors by the closed-loop speed control. The strip is transferred from upstream into the furnace zone, in which it is heated (or cooled), then passed through the B zone to the TM12 and finally sent to downstream by the rolls. The strip of different specification is required to be heated to different temperatures at different sections by the annealing technics. So the line has to speed up or decelerate frequently when it changes the strip specifications it produces.

As shown in Fig. 1, the length of the strip between two adjacent rolls is long. In addition, to meet each section’s technological requirement, different types of rolls and drives are located: the anterior 20 rolls are A zone rolls, and the next roll is the B zone roll, the next two rolls are the BR (bridle rolls) in B zone, the 24th roll is a tension meter roll also used as the tension measurement (TM12). The inertias and diameters of different types’ rolls and the relevant convertor output power maximum are different. So, to make sure the synchronizations of each roll’s speed response when the line speeds up or decelerates, each roll’s ASR gain is set up respectively.
B. Process Model

First of all, based on the torque-balance principle of the roll and tension-building principle, the tension model is derived as follows:

\[
\begin{align*}
F_i(s)/(v_{i+1}(s) - v_i(s)) &= K_i/(s + C_i) \quad (1) \\
T_o(s) - [F_i(s) - F_{i+1}(s)]R_i - T_{\beta i} &= J_i s \phi_i(s) \quad (2) \\
v_i(s) &= \omega_i(s) \times R_i \quad (3) \\
T_{\beta i} &= \xi \phi_i \omega_i \quad (4) \\
T_{\beta i} &= \xi \phi_i \omega_i \quad (5)
\end{align*}
\]

where \( K_i = E S / L_i \) stands for strip elasticity and where \( C_i = v_i / L_i \), \( F_0 \) denotes entrance tension TM11, \( F_i(i = 1, 2, ..., 23) \) denotes tension between two adjacent rolls, \( F_{24} \) denotes exit tension TM12; \( v_i \) is each roll’s line-speed, \( T_{\beta i} \) is the no-load torque, \( \omega_i \) is the angular velocity of each roll, \( J_i \) is the overall inertia of the roll, motor and strip, \( R_i \) is the roll radius, \( L_i \) is the distance between adjacent rolls, \( S = w \times h \) stands for strip cross-sectional area, where \( w \) and \( h \) are the strip width and strip thickness respectively, \( E \) is the strip elastic modulus. The object model is shown in Fig. 2, from which we can see that the rolls are coupled by the strip.

The main differences between the tension object established above and the CAPL simple object model in [2] are that the axle tree friction and strip inertia’s effects are taken into account when modeling. To explain the necessity of high-accuracy speed control and roll-speed response synchronization (4), and the related factors (roll inertia (1), strip inertia (3) and axle tree friction (2)), we describe the following four points in detail, which are also the next section foundations of designing the gain scheduling adaptive control scheme:

1. Select the controller parameters according to the rolls’ different inertias

The inertias of each roll may be different, that is \( J_1 \sim J_{21} = C_1 \), \( J_{22} = C_2 \), \( J_{23} = C_3 \), \( J_{24} = C_4 \), while \( C_1 \neq C_2 \neq C_3 \neq C_4 \neq 0 \) are constants. And to benefit the roll-speed response synchronization (i.e. the same response time), the motors’ output torque is required to be proportional to the load inertia. So the converters’ torque constant \( \xi \phi_i \) and the speed-loop control gain \( K_{ni} \) are set respectively, to satisfy \( \xi \phi_i \times K_{ni} / J_i = C_i \), while \( C_j \) is another constant.

2. The no-load torque is related with the roll-speed.

No-load torque current is the torque current used to overcome the friction torque when the motor with the roll rotates with no load, that is \( I_{\beta i} = I_{\beta i} + I_{f, \text{ni}} \), which contains two parts: the motor bearing friction \( I_{f, \text{ni}} \) and the roll bearing friction \( I_{\beta i} \). The bearing friction is non-linear related with the roll speed, and the greater speed, the greater bearing friction. The relationship between the no-load current and speed can be estimated by the current and speed data collected during the no-load experiment.

3. Influence of the strip inertia should not be ignored when the units accelerate or decelerate.

Compared to the rolling process, its strip length between the adjacent rolls is much longer; Compared to the paper-making process, the density of the chip is much bigger. So the length of the strip between two rolls is long and the density of the material is big. And considering that the continuous annealing process requires regulating the speed frequently, and the fact that when the units accelerate or decelerate, not only the roll-speed alters, but also the strip-speed alters as the strip is attached to the roll. The strip inertia should not be ignored when modeling. From this point of view, the \( J \) in the model not only consists of the motor inertia and the roll inertia as a whole, it also contains the strip inertia. That means \( J \) is composed of three parts,

\[
J = J_0 + J_1 + J_M + J_R + J_s
\]

where \( J_1 \) - strip GD\(^2\), \( J_0 \) - machine GD\(^2\), \( J_M \) - motor GD\(^2\).
\[ J_g \text{-roll GD}^2, J \text{-machine GD}^2 \text{ and strip GD}^2 \]

where

\[ J = P \times S \times L \times R^2 / G^2 \]  \hspace{1cm} (7)

\[ P, L, G \] are the strip density, the strip length and the reduction-speed ratio respectively.

(4) Small deviations of the speed cause large tension fluctuations, because of the larger strip elasticity.

We can compute the strip elastic modulus by 

\[ E = (208570 - 0.209664t^2) \times 10^6 \text{ N/m}^2 \] when the temperature is \( t^\circ\text{C} \), and compute the elasticity coefficient by

\[ K_i = E \times S / L_i \] (take A furnace as an example, \( t = 300^\circ\text{C}, \ L = 20\text{m}, \ S = 0.233 \times 851 \text{mm}^2, \ K_i = 2089682.5 \text{ N/m}) \]

then we can conclude that small speed deviations will cause large tension deviations by Eq. (1).

III. GAIN SCHEDULING ADAPTIVE CONTROL ALGORITHMS

A. Control Algorithms

Tension control has a lot of applications in the process industry, such as paper-making process, tape-sending process, cold-rolling process, tinning process and so on. For these tension objects, the corresponding object model, a number of control algorithms and tension soft-sensor methods were set up. For example, a tension object model for the high-speed low-tension tape transfer process was established in [1], and simple tension object model was established in [2], an observer-based tension control method for continuous strip production was established in [3], and a tension control system based on cells or dancer roll regulation in paper machinery was established in [4]. However, these object models and control algorithms established above did not consider the effect of axletree friction and strip inertia.

In order to make the tension stable at TM11, we design a cascade closed-loop tension control method based on the speed regulation, as shown in Fig. 3. The outer is the tension loop, in which the tension controller regulates several rolls’ speeds simultaneously to control the TM11 tension. The inner is a speed-current double-closed-loop with voltage vector-based PWM convertor and the motor, shown in Fig. 4. And the tension controller ATR, speed controller ASR both adopt the digital PI algorithm, as shown below,

\[ u(k) = K_p \left( e(k) + \frac{T_s}{T} \sum_{j=0}^{k} e(j) \right) + u_0 \]  \hspace{1cm} (8)

where \( u(k), e(k) \) of the tension loop(ADR) and the speed loop (ASR) are calculated respectively. Besides, in order to avoid the large load focusing on a single roll, it is necessary to make bridle rolls’ loads balanced. So we define a new control index to describe this control target, as shown in Eq. (9). To achieve this goal, we add the LOAD BALANCE algorithm for the furnace bridle rolls, as shown in Fig. 3. The outputs of the ACR \( I_{a22}, I_{a23} \) are fed back to LOAD BALANCE controller, whose output is the compensation value \( v_{lb,c} \)

computed by Eq. (11). Then we get the speed setting value \( v_{sp} \) by add \( v_{lb,c} \) and tension compensation value \( v_{i,c} \) to the benchmark speed MRH, as shown in Eq. (10).

\[ \text{Opt: Min} \left( \| I_{a22} - I_{avg} \| + | I_{a23} - I_{avg} | \right) \]

\[ \begin{align*}
    v_{sp} &= \text{MRH} + v_{i,c} + v_{lb,c} \\
    v_{lb,c} &= \begin{cases} 
        v_{lb\_max} & \text{if } v_{lb,c} > v_{lb\_max} \\
        K_b (I_{avg} - I_{avg}) & \text{else} \\
        v_{lb\_c} \leq v_{lb\_max} 
    \end{cases}
\end{align*} \]  \hspace{1cm} (11)

where \( I_{avg} = (I_{a22} + I_{a23}) / 2 \) is the torque-current average value of the bridle rolls \( 22R, 23R \), and \( K_b \) is the ratio factor.

B. Gain Scheduling Adaptive Control Strategy

As CAPL (Continuous Annealing Process Line) includes furnace zone, in which the higher temperature would make tension stress limit decline rapidly (from 400MPa reduced to about 50MPa), it is essentially necessary to make sure high performance of the tension control and synchronization of the roll-speed. And the continuous annealing process changes raw materials frequently, making the traditional PID control’s performance can not be satisfying. In this situation, the adaptive control scheme is often proposed, in which the controller parameters be adjusted to compensate the change of production conditions, such as the adaptive control during the continuous casting process [5] and the tension control of POR (pay-off Reel) [6] during continuous annealing process in iron and steel industry, and the gain scheduling adaptive method applied for nonlinear controller design in flight control and automotive engine control [7]. As for the continuous annealing line: the axletree friction change’s influence on roll-speed control precision is wicked; the strip inertia’s influence on the roll-speed control dynamic performance is also bad. That is to say, the tension system could hardly achieve the ideal performance if it adopts the invariable feedforward value and invariable speed controller gain, because not only the friction torque varies when the line regulates speed, but also the strip inertia varies when the line producing different specification strip. So in this paper, by adjusting the ACR setting value and ASR gain value in an adaptive manner based on the selected assistant variables (strip width, strip thickness and roll speed), we design a gain scheduling adaptive control method to compensate for the changes of the friction torque and the strip inertia.

1) Friction Torque Current Feedforward Compensation:

From the object model analysis above, we can see that, the roll’s friction torque is different when the line is running at different speed. To compensate for the no-load torque of the roll which is nonlinear related with the roll-speed, we design a gain scheduling feed-forward compensation algorithm. We set the parameter \( I_{ref} \) to the corresponding convertor as shown in Fig. 4, to compensate for the disturbances caused by the change of the no-load torque when the units run at different speed.
2) Strip Inertia Gain Scheduling Adaptive Compensation:

From the tension control diagram shown in Fig. 3, we can see that the rolls’ speed are regulated synchronously by the tension closed-loop control when there are disturbances near the tension sensor. In addition, from the object model analysis, we come to the conclusion that the effect of the strip inertia should not be ignored when the line accelerates or decelerates. Considering these, we design a gain scheduling adaptive control method to compensate for the inertia’s influence on tension control when producing different specification strip [8]-[9], eventually ensure the synchronization of the speed regulation when the line accelerates or decelerates. In this scheme the ASR controller gain $K_s$ is adjusted adaptively according to the produced strip mass (determined by the strip width and thickness), to compensate for changes of the process conditions.

As for the adaptive control of the continuous annealing system, the operating condition is the strip specification (width, thickness) when the technology section changes the MRH. The implementation scheme of the speed-loop gain compensation is shown in Fig. 4, in which the speed-loop gain can be $K_o$ obtained by Eq. (12) when producing specifications ($w, h$) strip:

$$K_o / J_o = K_s / J \Rightarrow K_s = (J / J_o) \times K_o$$ (12)

where $K_o$ is the speed-loop gain when no strip, $J_o$ is the inertia of roll inertia and motor inertia, $J$ is the overall inertia considering the strip inertia, in which $J_s$ is the strip inertia relative to the bearing, achieved by Eq.(7).

![Fig. 3. Tension control for TM11](image)

**IV. SIMULATION TESTS**

We set up the tension control system simulation platform in Matlab / Simulink environment based on the developed object model and control scheme mentioned above, in which the discrete - continuous combined simulation manner is proposed to make the simulation model be in accordance with the actual process: the simulation procedures adopt the digital controller similar to the PLC procedures, with the sample time $T_s = 0.02s$; the object model is 4-5 Runge-kutta (ode45) continuous-time model. In addition, as described below, the simulation system’s controller parameters, object model parameters, the line’s speed regulation mode and strip specifications etc are all consistent with the actual process.

**A. Roll Speed Step Tests**

There are four categories rolls between TM11 and TM12. The speed-loop gain was set respectively according to the roll inertia, with the parameters and speed loop gain values shown in TABLE I.
To compare the speed-loop control performance with and without the friction torque gain scheduling compensation, we establish the object model of the 2R and the control model for it as an example, with the variable $I_f$ computed by Eq. (13) to compensate for non-linear function of the friction torque in the feed-forward control. We do speed step test (590-600m/min) with and without compensation, whose results are shown in Fig. 5.

As shown in Fig. 5, after the friction torque gain scheduling compensation applied to the speed control system, the control accuracy of the speed loop is improved. That will also be conductive to ensure synchronization roll-speed regulation.

$$I_f = \begin{cases} 
0.3 + v/110 & 0 \leq v < 44 \\
0.7 + 3v/440 & 44 \leq v < 88 \\
1 + v/176 & 88 \leq v < 264 \\
2 + v/880 & 264 \leq v < 440 \\
2.2 + 3v/4400 & 440 \leq v < 880 
\end{cases}$$  
(13)

**TABLE I**

<table>
<thead>
<tr>
<th>Roll</th>
<th>$R$ (mm)</th>
<th>$J_0$ (kg.m²)</th>
<th>$G_r$</th>
<th>$\xi\phi$ (N.m/A)</th>
<th>$K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1R~21R</td>
<td>200</td>
<td>14.13</td>
<td>1</td>
<td>5.693</td>
<td>1/160</td>
</tr>
<tr>
<td>22R</td>
<td>200</td>
<td>15.097</td>
<td>1</td>
<td>4.35</td>
<td>1/120</td>
</tr>
<tr>
<td>23R</td>
<td>200</td>
<td>15.887</td>
<td>1</td>
<td>4.651</td>
<td>1/120</td>
</tr>
<tr>
<td>TM12 (24R)</td>
<td>300</td>
<td>4.276</td>
<td>3.462</td>
<td>2.898</td>
<td>1/120</td>
</tr>
</tbody>
</table>

B. **Line Speed-Regulation Tests**

We also pay attention to the system performance with and without the strip inertia adaptive compensation respectively, when we do tension step test and units speed adjustment test for producing the strip of 1.2m wide, 0.27mm thick, with the model parameters shown in TABLE II.

**TABLE II**

<table>
<thead>
<tr>
<th>$E$ (GPa)</th>
<th>$L$ (m)</th>
<th>$w$ (mm)</th>
<th>$h$ (mm)</th>
<th>$K_p_S$</th>
<th>$K_I_S$</th>
<th>$K_p_T$</th>
<th>$K_I_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>210000</td>
<td>20</td>
<td>1.2</td>
<td>0.27</td>
<td>4200</td>
<td>50</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

1) **Tension Step Test**: In the 100s, we simulate the step regulation of the tension (1750->2000N) in two cases: with compensation and without compensation, and pay attention to the dynamic characteristic of this system, as shown in Fig. 6. From that we can conclude that after we apply the gain scheduling adaptive compensation control algorithms, the stability of the tension closed-loop control is improved as the tension fluctuations is smaller and the adjustment time is shortened.

2) **Units Speed Adjustment Test**: Simulate the practical speed adjustment condition: after the system is in steady-state (30s), we pay attention to tension $F_2$ (tension ahead the B BR) when the benchmark speed MRH was increased to 700mpm from 500mpm by slope ($a = dv/dt = 200mpm/s$, 1mpm=1m/min), as shown in Fig. 7. As can be seen, because of the adjacent rolls’ speed-mismatch with no inertia compensation, the extent of tension fluctuations is large, and which is effectively restrained by the inertia compensation.

**V. **INDUSTRIAL APPLICATIONS**

Apply this gain scheduling adaptive control method to a CAPL in China. Pay attention to the conditions of the fluctuations of the tension and the load current when the line accelerates or decelerates before and after using this method. When going on the tests, the line is producing the same specification’ strips (width 0.203mm, thickness 0.813m) and the tension setting and the annealing arts and crafts are all the same, and the interval between the two tests is short, i.e. the furnace conditions are almost the same.
The results with this method and without this method are shown in Fig. 8, in which the curves of the tension and the drive-load by applying this method can be seen in A, and the curves of the tension and the drive-load without this method can be seen in B. From that, we can see the fluctuations of the tension are $F_{t1} = 350\text{N}, F_{t2} = 100\text{N}$ respectively before and after applying this method, and the fluctuations of load current decrease obviously to 10% from 100%.

VI. CONCLUSION

In this paper, the tension object model with the roll, motor friction and the strip inertia is established and a gain scheduling adaptive control algorithm with feed-forward friction compensation and speed loop gain scheduling compensation is designed and applied to this model. Simulation results show this method could help the line get better performance during acceleration and deceleration periods, and restrain the tension variation effectively. From the effect of industrial application, we can conclude that this method is not only effective in inhibiting tension fluctuations and load fluctuations, but also helpful to reduce the impact and regulation time when the units accelerate and decelerate, so that the units could run in better condition reliably and stably, and conducive to the improvement of the system stability. This method could also be extended to other similar units and places where demanding speed synchronization and inertia compensation. For this unit as well, it could also be applied to the looper-rolls, driver-rolls and bridle-rolls.

REFERENCES