A Web Tension Control Strategy for Multi-span Web Transport Systems in Annealing Furnace

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This paper presents a web tension control strategy for multi-span web transport in a continuous annealing process (CAP) used in steel manufacture. In the CAP, the temperature of the steel web is varied over a wide range, and this generates a thermal strain in the web. In addition, in order to save workspace, vertical type web transport systems are usually used, and the weight of the web causes a gravity strain in the web. These strains in the web induce the variation of the web tension. To control the web tension in the CAP, a feed-forward tension control scheme is suggested, which is based on a mathematical model considering the additional strains due to thermal and gravity effects. The performance of the proposed feed-forward tension control scheme is experimentally evaluated in an actual CAP. In addition, to respond to the variations of many system parameters, a feedback tension control scheme based on the tension observer is proposed. The performance of the feedback tension control system is evaluated by computer simulation.

KEY WORDS: web transport system; continuous annealing process; feed-forward tension control; feedback tension control.

1. Introduction

Annealing processes, in general, consist of heating, soaking, cooling and over-aging furnaces. The annealing process is executed continuously through web transport systems (WTS), so it is known as a ‘continuous annealing process (CAP)’. A web break or fold can occur by the variation of the web tension. If a web break or fold occurs, then the production line has to stop and as a result, productivity decreases. Therefore, the web tension in the WTS has to be regulated to transport materials with satisfaction.

The web tension control of a multi-span WTS is difficult because the characteristics of the system dynamics depend on many system parameters which often vary over a wide range. In general, two kinds of web tension control are used in web processing industries: open-draw control and closed-loop control. In the “open-draw control” scheme, the web tension is controlled in an open loop fashion by regulating the velocities of the rollers at the end of the web span. The closed-loop control scheme is based on the detection of the web tension. In either case, it is very important to minimize the instantaneous tension variation of the web.

In a previous research, 2–4) a web tension model with thermal and gravity effects was proposed. Lee and Shin (referred paper) proposed a mathematical web tension model considering temperature variation. An extended mathematical web tension model considering gravity effect was suggested by Kim. In these papers, a feed-forward web tension control scheme based on the proposed web tension model was presented and the performance of the feed-forward web tension control scheme was evaluated by computer simulation.

In this paper, through experimental results obtained from an actual CAP, the performance of the feed-forward web tension control scheme based on the proposed web tension model is evaluated. In addition, in order to cope with the variation of many system parameters, a feedback web tension control scheme based on the web tension observer is proposed. Through computer simulation, the variations of the width and thickness of material are considered and the performance of the feedback web tension control scheme is evaluated.

2. Configuration of the Continuous Annealing Process

A typical configuration of the CAP usually consists of the pre-heating section (PHS), the heating section (HS), the soaking section (SS), the cooling section (CS), the over-aging section (OAS) and the final cooling section (FCS). Each section has a heating or cooling furnace, as shown in Fig. 1. The heat pattern of the annealing process is determined according to the composition and the product grade of the steel strip. Figure 2 shows the typical heat pattern of annealing processes. The wide range variation of the temperature causes thermal strain, which changes the properties of materials such as the elastic and thermal coefficients. In addition, the WTS for mass production is a very large-scale plant. In order to save workspace, the WTS is usually
constructed vertically in the industry, and the weight of web in this configuration causes gravity strain. Therefore, the web tension always varies in the CAP.

A WTS, which consists of 44 rolls except the helper roll and 44 spans, in a CAP is considered, as shown in Fig. 1. The web transport velocity and web tension are regulated by the motor for the roll drive. The web velocity is controlled by all the rolls, and the web tension is controlled at the outlet span with the tension meter in each furnace. In order to regulate the web tension, the whole process is divided into five tension control groups according to the position of tension meters. A temperature variation section with a heating or cooling furnace exists in the CAP. It is very difficult to establish a tension meter in each furnace. In addition, a sensor established in the furnace where the temperature varies greatly has a very high possibility of malfunction. Therefore, to compensate for the lack of the tension meter, a group web tension control has been considered.

Figure 3 shows a schematic diagram of the web tension control system in the PHS and HS. This control system can be distinguished by the two tension control groups based on tension meters 1 and 2. The information from the two tension meters, which are attached to the 6th and 22nd spans, is applied to the 22 velocity controllers (ASR1–ASR6 and ASR7–ASR22) according to the velocity information sent to all the rollers through the two web tension controllers (ATR1 and ATR2). ATR1 offers its output information to ASR1–ASR6 and ATR2 offers its output information to ASR7–ASR22. In the 1st tension control group, the information of web tension meter 1 directly affects only ASR6 through the ATR1 and the others, with the exception of the ASR6, are indirectly affected. The 2nd tension control group works in the same manner as the 1st tension control group. Therefore, only the 6th and 22nd rollers can effectively control the tension of the web. For these reasons, the web tension control loops with a tension meter can be explained as the closed loop structure, and the other web tension loops without a tension meter can be explained as the open loop structure. The web passing in the CAP has additional strains due to thermal and gravity effects as well as the general elastic strain. These strains cause the web tension variation of WTS in the CAP. Therefore, to reduce the web tension variation effectively, the velocity of rolls that have the open loop control structure should be regulated.

3. Mathematical Model of WTS

3.1. Basic Model of the Web Tension

The standard model for web tension control has been presented in numerous papers.\textsuperscript{5–9} It is built from the equations describing the web tension behavior between two consecutive rolls and the velocity of each roll. The relationship between the strain and the velocity of the web can be expressed as
where $e_{eq,N}$ is the average strain in the control volume

$$e_{eq,N} = \frac{1}{L_N} \int_{0}^{L_N} e_N(x,t) dt$$

and subscript $N$ is a number of spans. If the strain is uniform within the web span, then Eq. (1) can be expressed as

$$L_N \frac{d}{dt} e_{eq,N}(t) = -e_{eq,N}(t)v_N(t) + e_{N-1}(t)v_{N-1}(t) + v_N(t) - v_{N-1}(t)$$

(2)

Applying Hooke’s law to Eq. (2), the relationship between the tension and velocity of the web can be represented as

$$L_N \frac{d}{dt} T_N(t) = -T_N(t)v_N(t) + T_{N-1}(t)v_{N-1}(t) + AE(v_N(t) - v_{N-1}(t))$$

(3)

where $A$ and $E$ are a cross-section area and Young’s modulus of span, respectively.

From Eq. (3), it can be found that the tension in the web span is created by the difference in velocity between the web spans, according to the incoming web tension. Equation (3) can be usefully applied for the WTS in steady-state. However, Eq. (3) is not suitable for the WTS in the CAP in which the effects of the temperature and gravity of the steel web have to be considered.

3.2. Model of the Web Tension with Consideration of Thermal and Gravity Effects

A novel model with additional strains due to thermal and gravity effects, respectively, is extended from the basic model. It is derived by considering the additional strains, equivalent Young’s modulus and the thermal coefficient. The detailed description of the novel model was given in the previous research.4) In the novel model, the relationship between web tension and web velocity is given by

$$L_N \frac{d}{dt} e_{eq,N}(t) = (e_{N-1}(t) - 1)v_{N-1}(t) - (e_N(t) - 1)v_N(t)$$

(1)

where $e_{eq,N}$ is the average strain in the control volume

$$e_{eq,N} = \frac{1}{L_N} \int_{0}^{L_N} e_N(x,t) dt$$

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3.3. Web Velocity on Each Roll

Assuming that the web does not completely slide on the roll, the web velocity is equal to the roll linear velocity. The velocity $v_N$ of the $N$th roll can be obtained from the torque balance on the roll. The general dynamics of the roll of a vertical type WTS can be expressed as

$$J_N \frac{d}{dt} v_N = -b_N v_N + R_N(T_N - T_{N-1}) + K_{mot}U_N + C_i$$

(5)

where $b_N$ is the viscous coefficient of motor, $K_{mot}U_N$ is the motor torque, $J_N$ is the roll inertia, $R_N$ is the roll radius and $C_i$ is the sum of the friction torques.

4. Design of the Web Tension Control System

4.1. Design of the Feed-forward Web Tension Control System

Figure 4 shows the block diagram of the web tension control system for a single span in a CAP. This is a cascade control system, which consists of an automatic speed regulator (ASR) of the inner loop for web speed control and an automatic tension regulator (ATR) of the outer loop for web tension control. This control system can effectively improve the system performance beyond that achieved by the single-loop control.10) The inner and outer loops control the roll velocity and the web tension, respectively.

The feedback control laws for the ASR and the ATR are based on proportional-integral controls (PIC) as follows11):

$$U_{ASR} = K_{asr}e_r + K_a \int e_r dt$$

(6)

$$U_{ATR} = K_{atr}e_{tr} + K_a \int e_{tr} dt$$

(7)

where $e_r = v_{ref} - v_N$

$$e_{tr} = T_{ref} - T_N$$

The ATR makes the reference velocity for the ASR. This means that the velocity of the roller is regulated to prevent the variation of the web tension. The strain of the web in the CAP is influenced by thermal and gravity effects, as previously stated in Chap. 2. Under such influences, the tension of the web in the CAP becomes unstable. In this situation, it is impossible to achieve a desired web tension by

![Fig. 4. Block diagram of the web tension control system for single span in a CAP.](image)
using PI feedback controllers, which are described by only Eqs. (6) and (7). In order to more effectively prevent the variation of the web tension, a feed-forward velocity compensator has to be designed.

To effectively suppress the disturbance due to the variation of the temperature of the web in the CAP, it is important to apply a feed-forward velocity compensator as well as PI control schemes for the ATR and ASR tension feedback controls. The feed-forward velocity compensator can be derived from the novel model in Eq. (5). To design the feed-forward velocity compensator, it is assumed that the value of web tension in Eq. (5) expresses a steady state. Then,

\[
\frac{1}{L_N} \left[ -\frac{E_{eq,N}}{E_{eq,N}} T_N + A E_{eq,N} (1 - e_{eq,N}^{th} - e_{eq,N}^w) v_N \right. \\
+ \left. A E_{eq,N} \left( \frac{T_{N-1}}{A E_{N-1}} - 1 \right) v_{N-1} \right] = 0 \quad \text{...........................................(8)}
\]

or

\[
v_{N-1} = \frac{T_N}{\frac{A E_{eq,N}}{A E_{N-1}} - 1} v_N - \frac{T_{N-1}}{\frac{A E_{eq,N}}{A E_{N-1}} - 1} v_{N-1} \quad \text{..........................(9)}
\]

Equation (9) is related to the velocity of the 22nd roll, as shown in Fig. 3, which is called the ‘speed master roll’. The speed master roll provides the reference velocity to the 21st roll.

For instance, if there is a velocity difference between the 21st and the 22nd roll, then the web tension would vary in the 22nd span (between the 21st and the 22nd rolls). Specifically, if the web tension is varied by temperature and gravity effects at the 22nd span, the 21st roll needs to compensate for the velocity difference between the 21st and the 22nd roll. These processes continuously progress from the 21st span to the 1st span. Thus, the feed-forward velocity compensation value can be obtained by the velocity difference between the rolls as follows:

\[
v_{\text{feed-forward}} = v_{N-1} - v_{op} = \frac{T_N}{E_{eq,N}} - 1 + e_{eq,N}^{th} + e_{eq,N}^w \frac{T_{N-1}}{E_{N-1}} - 1 v_{N-1} - v_{op} \quad \text{.......................................(10)}
\]

Figure 5 shows the block diagram of the feed-forward web tension control system for a single span in a CAP.

### 4.2. Design of the Feedback Web Tension Control System

The feedback control structure is robust to disturbances and unexpected variations of system parameters. However, a feedback web tension control system for the spans in the furnace section is difficult to construct because of the lack of the tension meter. Therefore, in order to detect the tensions of the spans without tension meter, a tension observer should be designed. Because the web tension affects motor as a disturbance to the motor, the motor dynamics can be used to estimate the web tension. From Eq. (5), the tension of the web can be represented as

\[
T_{N-1} = T_N - \frac{1}{R_N} \left( \frac{J_N}{R_N} \dot{v}_N - K_{mot} U_N + C_f \right) \quad \text{........................................(11)}
\]

By the Laplace transformation of Eq. (11), the following equation can be obtained.

\[
T_{N-1}(s) = T_N(s) - \frac{1}{R_N} \left[ \frac{J_N}{R_N} s v_N(s) - K_{mot} U_N(s) + C_f(s) \right] \quad \text{........................................(12)}
\]

Since a differential term is included in Eq. (12), for implementation, we consider a low pass filter \(Q(s) = 1/(\tau_0 s + 1)\) where \(\tau_0\) is the time constant of the low-pass filter. Then,

\[
\hat{T}_{N-1}(s) = T_N(s) - \frac{1}{R_N} \left[ \frac{J_N}{R_N} s v_N(s) - K_{mot} U_N(s) + C_f(s) \right] \quad \text{........................................(13)}
\]

In addition, applying the equivalent conversion to Eq. (13), the estimated web tension can be described as

\[
\hat{T}_{N-1}(s) = T_N(s) - \frac{1}{R_N^2} \frac{1}{\tau_0} (1 - Q(s)) v_N(s) + Q(s)[K_{mot} U_N(s) - C_f(s)] \quad \text{.........................(14)}
\]

Figure 6 shows the feedback web tension control system with a tension observer. By using the tension observer, spans without the tension meter can realize a feedback control structure.
5. Experiment and Simulation of Web Tension Control Systems

5.1. Feed-forward Web Tension Control

The validity of the feed-forward web tension control strategy is experimentally evaluated in a real CAP in an industrial field. The web tension signal is measured only at the outlet span in each furnace and the current signals of the motor for the roll drive are measured with angular velocity meters at all the rolls. In order to find the relationship between the web tension variation and the current variation, computer simulation is executed. The number of spans in the PHS and HS is 22, and the temperature of the web varies from 30 to 790°C, as shown in Fig. 7. The system parameters of the WTS, which are shown in Table 1, are applied with the same values in the 22-spans, with the exception of the Young’s modulus and thermal coefficient due to the temperature variation.

Figure 8 shows the simulation results of the web tension control system without a velocity compensator. Figures 8(a) and 8(b) show the web tension error in the PHS and HS, respectively. The web tension is measured only at the 6th and 22nd spans, which are the outlet spans in each furnace. Therefore, at these spans, the web tension can be regulated very well, while the web tensions at the other spans in the furnace section are not regulated so they diverge. In actual systems, in order to prevent the excessive variation of web tension, a drooping loop is used. This loop connects the input and output of the ASR part with an adequate drooping gain to prevent the divergence of the motor current of the roll drive, and thus, to stabilize the web tension. However, this loop is not considered in this simulation.

Figures 8(c) and 8(d) show the tension of each span and
the motor current of each roll, respectively. Figure 8(c) shows that the span at the farthest distance from the tension meter has a relatively big tension error. In two control groups, the biggest tension error happens in the 3rd and 13th spans in the farthest spans from the tension meters. In addition, the web tension error occurs more frequently in the HS, because the HS involves a greater variation of the temperature and more numbers of spans than the PHS. From Fig. 8(d), which shows the motor current of each roll drive, it is found that the bigger the web tension error, the bigger the difference of the motor current.

**Figure 9** shows the simulation results of the web tension control system with a velocity compensator. The web tensions are regulated very well at all spans, as shown in Figs. 9(a) and 9(b). Figures 9(c) and 9(d) show the web tension error of each span and the motor current of each roll drive, respectively. When the web tension error decreases, the motor current of the roll drive has the same value at each roll. That is, if the motor current of each roll drive has a uniform value, the web tension is regulated. This result is used for evaluating the experimental results.

Because the CAP proceeds consecutively, an experiment is executed for a different steel strip, and the feed-forward velocity compensator is applied partially to the HS. **Table 2** shows the experimental condition of the web tension control system in the CAP. First, the performance of the feed-forward velocity compensator is evaluated through the experimental results for materials A1 and B1.

**Figures 10, 11 and 12** show the experimental results for the web tension control system in an actual CAP. Figure 10 shows the measured web tension errors at the outlet spans in the HS and PHS where tension meters are equipped. In two cases, the web tensions at the outlet spans are controlled within the tolerance error, as they were in the simulation results. Figure 11 shows the measured motor currents excited at each motor. In the case of no velocity compensation, the motor current at the inlet (7th) roll differs from that at the outlet (22nd) roll. This difference means that web tension error exists according to the difference of the

<table>
<thead>
<tr>
<th>System parameter</th>
<th>Notation</th>
<th>With velocity compensation</th>
<th>Without velocity compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-sectional area</td>
<td>A</td>
<td>0.001458 m²</td>
<td>0.002784 m²</td>
</tr>
<tr>
<td>Equivalent moment of inertia of the roller</td>
<td>J</td>
<td>2.96 kgm²</td>
<td>2.96 kgm²</td>
</tr>
<tr>
<td>Length of the web span</td>
<td>L</td>
<td>20 m</td>
<td>20 m</td>
</tr>
<tr>
<td>Radius of the roller</td>
<td>R</td>
<td>0.4 m</td>
<td>0.4 m</td>
</tr>
</tbody>
</table>
| Torque constant of the motor | $K_{oer}$ | 35.28 Nm/A                 | 35.28 Nm/A                   

**Fig. 8.** Simulation results of the web tension control system without velocity compensator.
motor current. In the case where velocity compensation is applied, the current of each motor has a uniform value, and web tension can be uniformly regulated. Figure 12 shows the motor current of each roll drive in 60 s. In Fig. 12, the current value excited at each roller is repeated up and down; this repetition is necessary to support the weight of the web in a vertical WTS.

Figure 13 shows the experimental results of the motor currents for material B1, B2 and B3 in the HS, where the feed-forward velocity compensator is applied. Figure 14 shows the histogram of experimental results of the motor currents in the HS and Table 3 shows the statistic analysis of the experimental current data. In Fig. 14 and Table 3, the

<table>
<thead>
<tr>
<th>Condition</th>
<th>Without velocity compensation</th>
<th>With velocity compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>A1</td>
<td>B1</td>
</tr>
<tr>
<td>Width</td>
<td>0.799mm</td>
<td>2.22mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>1826mm</td>
<td>1254mm</td>
</tr>
<tr>
<td>Strip size</td>
<td>1459mm²</td>
<td>2784 mm²</td>
</tr>
<tr>
<td>Line speed</td>
<td>115rpm</td>
<td>83rpm</td>
</tr>
<tr>
<td>Tension reference</td>
<td>630kgf</td>
<td>2184kgf</td>
</tr>
</tbody>
</table>

Fig. 9. Simulation results of the web tension control system with velocity compensator.

(a) Web tension error in the PHS

(b) Web tension error in the HS

(c) Web tension error of each span

(d) Motor current of each roll drive

Table 2. Experiment condition.

Fig. 10. Measured web tension error at the outlet spans in the PHS and HS.
A web tension control system with a velocity compensator has a uniform distribution of the motor current for each roll drive and the variance and standard deviation of the motor current are smaller than those of the web tension control system without a velocity compensator. From the above experimental results, it is found that the variation of the web tension of the spans in the furnace can be satisfactorily rejected by using the feed-forward velocity compensator. This result is verified by the motor current of each roll drive.

5.2. Feedback Web Tension Control Strategy

From the results in Sec. 5.1, it is found that the proposed feed-forward web tension control strategy can satisfactorily regulate web tension. However, if some perturbation exists in the furnace section, the feed-forward web tension control strategy may not be suitable. For example, an actual CAP is used to produce various kinds of steel products according to purpose and usage, and cold-rolled steel strips of various thickness and width proceed through this process. For example, the cross section area of materials is varied according to the kind of product.

The performance of the proposed feedback web tension control strategy is evaluated through computer simulation. System parameters used in the feed-forward web tension control strategy are applied in the simulation. Figure 15 shows the simulation results of the feedback web tension control system with the tension observer. By using the tension observer and individual feedback controller, web tension variations can be effectively rejected in all the spans that exist in the furnace section.

Figures 16 and 17 show the simulation results of the feed-forward and feedback web tension control strategies...
Fig. 15. Simulation results of the feedback web tension control system with tension observer.

(a) Web tension error in the PHS
(b) Web tension error in the HS
(c) Current of motors of each roll drive
(d) Web tension error of each span

Fig. 16. Simulation results of the feed-forward web tension control system according to the variation of the cross section area.

(a) Web tension error of each span
(b) Current of motor of each roll drive

Fig. 17. Simulation results of the feedback web tension control system according to the variation of the cross section area.

(a) Web tension error of each span
(b) Current of motor of each roll drive
considering the variation of the cross section area, respectively. In the feed-forward web tension control system, if the cross section area of the material varies, the web tension in the furnace section varies. In addition, the smaller the cross section area of the material, the more the variation of the web tension. That is, thin steel plates of small cross sectional area may be deformed easily according to the temperature variation, and the web tension varies more frequently. In the feedback web tension control system, web tension is regulated very well according to the variation of the cross sectional area. Through the simulation results, it is found that the feedback web tension control system can satisfactorily regulate the web tension in the furnace section. However, in order to apply the feedback control system to real systems, it is very important to accurately model the actual plant. Therefore, the real CAP must be implemented carefully. This would provide a sufficient framework for future studies.

6. Conclusion

Feed-forward and feedback web tension control strategies were proposed to improve the performance of the conventional web tension control system in the furnace sections, which have a structural shortcoming due to the limitation of the number of tension sensors. The feed-forward velocity compensator is based on a novel mathematical model for web transport systems. From the experimental results obtained from the execution of a real CAP, it was verified that the web tension variation due to temperature and gravity effects can be effectively eliminated by feed-forward velocity compensation. In addition, the feedback web tension control strategy based on the tension observer was proposed. By using the tension observer, the web tension control structure in the furnace section was modified to a feedback control structure. Through simulation results, it was found that the feedback tension web control strategy can satisfactorily regulate the web tension in the CAP in spite of the variation of system parameters.

REFERENCES