CONTROL OF STRIP TENSION IN THE HEATING/COOLING SECTIONS OF CONTINUOUS ANNEALING LINES USING MODEL-BASED TENSION ESTIMATION

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ABSTRACT

Continuous annealing lines are productive manufacturing lines used by steel making companies for the manufacture of thin steel sheet products. In these lines, the steel strip is continuously heated and cooled depending on the heat processing cycle required for a particular product. The heating/cooling cycle plays a critical role in programming the material properties of sheet products. The annealing furnace consists of several heat transfer sections, such as heating section, soaking section, rapid cooling section, and cooling section. By transporting the steel strip through the annealing furnace, concentrated uneven stress in the strip resulting from cold rolling process is relieved and new material property specifications, such as tensile strength, yield strength or ductile strength, are obtained.

To improve transport behavior through the furnace, all the rollers are independently driven by a motor which are used to control strip speed and tension. Although rotational speed is measured for each driven roller shaft, tension measurement is spatially intermittent and located between any two heat transfer sections because of the inability to reliably measure tension within each heat transfer section. Since tension measurement is not available within the heat transfer sections, control of tension is challenging in these sections. An algorithm that provides tension estimation within each transfer section based on the model and tension measurements between each section is beneficial in regulating tension within acceptable levels in each section. In addition, due to heating/cooling of the strip during transport, changes in the physical and mechanical properties of the strip material must be accounted for in the design of tension control systems. In this paper, a dynamic model that provides the speed and tension behavior of the transported web through the heating or cooling section will be developed. Based on this model a tension observer will be designed for estimation of tension in each of the spans within the heat transfer

section. A control system for each driven roller will be designed to regulate web speed and tension and results of computer simulations of the model and the control system will be presented and discussed.

NOMENCLATURE

A : Area of cross section of strip
B_f : Bearing friction coefficient of roller
E : Elastic modulus
J : Roller inertia
K_m : Combination of motor torque constant and gear ratio
L : Span length of strip
R : Radius of the roller
t : Time
t_i : Strip tension in i^{th} span
v : Transport speed of strip on roller
x : Strip transport direction
z : State vector
α : Thermal coefficient of expansion
ε : Strain
θ : Temperature
τ : Motor torque input
ω : Angular speed of roller

Superscripts:
m : Tension dependent term
θ : Temperature dependent term

Subscripts:
i : Span or tension zone index
eq : Equivalent term
L : Pertaining to $x = L$
o : Pertaining to $x = 0$

INTRODUCTION

The goal is to develop a tension control strategy for control of tension in the steel strip transported through the heating and cooling sections of continuous steel processing lines, such as continuous annealing lines (CAL) and continuous galvanizing lines (CGL). A model-based control design strategy will be considered to develop a tension control system that can precisely control tension when there are disturbing forces on the strip due to heating/cooling of the web and machine imperfections. An important aspect to consider in the model development is the incorporation of thermal strain induced in the steel strip as a result of heating/cooling of the web. Since thermal strain affects the transport behavior and tension in particular, a nonlinear governing equation for tension that includes the temperature distribution in the steel strip will be considered.

It is critical to control the strip tension in a stable manner within the acceptable tolerance range in the steel strip processing lines. There are many factors that may lead to poor tension control. For example, due to heating/cooling of the strip during transport, there are changes to the physical and mechanical properties of the strip material that must be accounted for in the design of tension control systems. In particular, changes in the strip elastic modulus due to heating/cooling of the web can result in poorly performing tension control systems if fixed gain controllers such as the traditional PI controllers are employed.

Another aspect is the slip between the steel strip and the roller surfaces can cause severe defects such as scratches on the surface of the steel strip. This may be either due to an unresponsive tension control system or tension variations induced by a variety of process or machine conditions, including the heating/cooling process, non-ideal rollers, friction, etc. Even a small amount of slip over a long period of time in an annealing furnace can cause very small but severe dent marks which result due to the clod of strip constituent elements. It may be possible to avoid slip by increasing reference tension, but this is not desirable as conservative high tension operation reduces the life cycle of the equipment used to transport the strip. Conservative high tension operation is believed to have the merit of minimizing slip under tension control transient conditions. But high tension aggravates the sink roll grove marks on the steel strip as well as reduction of durable life of the sink roll bearing due to aggravated wear. Ensuring that there is minimal slip with proper tension control is necessary to prolong the life cycle of the equipment and produce defect-free exposed quality steel strips, such as those used for automotive steel products. Therefore, it is essential to select an optimal tension reference level and design a precise tension control system that can achieve the tension reference in the face of many material property changes and dynamic conditions.

A precise model that is capable of predicting the transport tension behavior will significantly assist in the analysis of transport behavior and development of tension control systems. Since the strip is undergoing changes during transport, an adaptive tension control system that can adapt to these changes in real-time while maintaining precise strip tension reference level has the potential to significantly improve performance over what is currently achievable with the existing tension control systems.

There has been considerable amount of work in the literature related to modeling and control of the transport behavior of moving webs on rollers through process machinery, including transport of metal webs such as steel and aluminum. Modeling and control related work for continuous strip processing can be found in [1–3]. Shin proposed a tension development mechanism in the continuous web line and tension control method based on classical control theory [4]. Shin also proposed a modified tension mechanism for strip in the annealing furnace which has various temperature distributions according to a heat treatment pattern and devised a control input calculation method for optimum tension control under the continuous annealing furnace environment [3]. An observer based control strategy for a continuous strip processing line based on the development of a model is given in [1]. Work specifically related to modeling and control of accumulators in continuous strip processing lines is given in [2, 5]. Recent work related to the development of model based nonlinear and adaptive tension control algorithms for moving webs can be found in [6–8]. Dwivedula discussed nonlinear characteristics such as backlash in the mechanical transmission system, slip between strip and roll, and strip compliance in the web transmission system, and investigated the effects of these characteristics on tension control of moving webs [6]; an adaptive tension controller design is proposed for decentralized control of web processing lines and compared the results of application of adaptive method to one of the traditional control methods such as the PID controller. A method to design stable decentralized controllers for web processing lines is given in [7]. A model reference adaptive controller for web processing lines based on a new reference model for large-scale systems is proposed in [8]. A method for adaptive redesign of reduced order observers for nonlinear systems with parameter adaptation is presented in [9]. Recent work on developing temperature distribution models in moving webs due to the application of different heating and cooling sources, such as heat transfer rollers, ovens, radiative heating, etc., can be found in [10–12].

ANALYSIS OF CGL/CAL ANNEALING FURNACE AND MODELING OF TRANSPORT BEHAVIOR

Continuous galvanizing/annealing lines are highly productive manufacturing lines used by steel making companies for the manufacture of thin steel sheet products. In these lines, the steel strip is continuously heated and cooled depending on the heat processing cycle required for a particular product. The heating/cooling cycle plays a critical role in programming the material properties of sheet products. The annealing furnace is the main processing section of a CGL/CAL and is divided into several heat transfer sections, such as heating section (HS), soaking section (SS), rapid cooling section (RCS), and cooling section (CS) as illustrated in Figure 1. By transporting the steel strip through the annealing furnace, concentrated uneven stress in the strip resulting from the cold rolling process is relieved and new material property specifications, such as tensile strength, yield strength or ductile strength, are obtained for the steel strip depending on customer orders. To obtain the designed material properties with good productivity and quality, steel web transport system, which comprises of driving motors for roller, strip tension measurement equipment, and heating and cooling equipment, has to be designed and controlled with the consideration of various key factors that aid in efficient transport of the steel strip through the annealing furnace without defects.

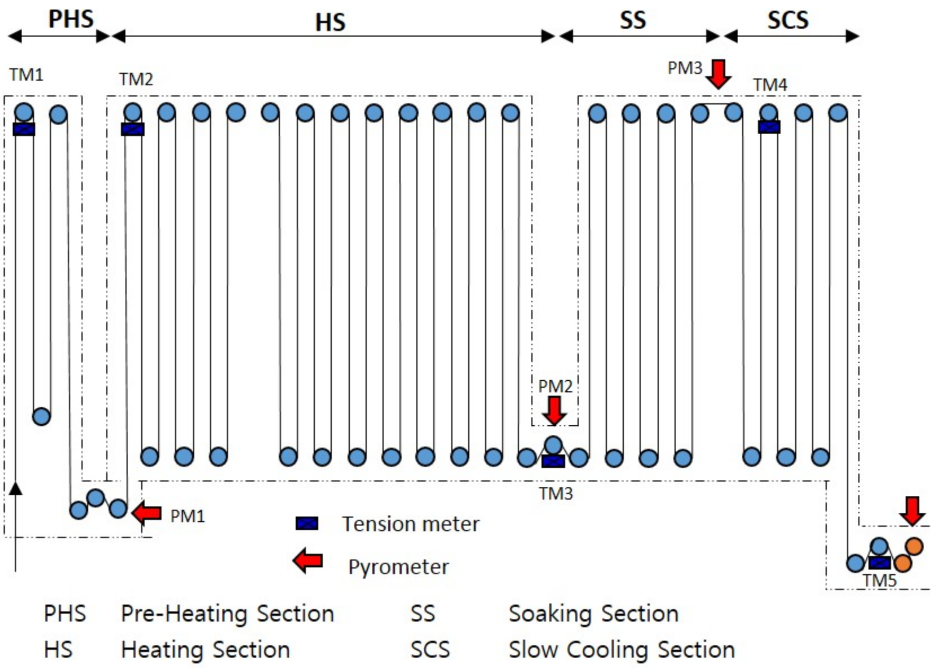

Figure 1 – Sketch of heating/cooling sections of an annealing furnace

Steel strip transport in annealing furnace

During transport of the steel strip in the annealing furnace, the strip experiences heating and rapid cooling that is called quenching. In the heating section, the strip temperature may reach up to 800 °C which makes the strip soft during transport and reduces its mechanical strength. As a result the strip properties and its transport behavior are sensitive to tension fluctuations. Because of this sensitivity to tension fluctuations, the strip tension in the heating section and other high temperature sections is maintained as low as possible but adequate enough to facilitate transport. Even in low tension transport, there are many possibilities for generating scratches on the strip surface due to slip between the strip and the roll surface. To avoid such surface defects, an electro-mechanical roll driving system comprising of combination of roll driving motors and tension measurement sensors is used. In the past, driven rollers were sparsely installed in the driving system, for example one motor for every 4 rolls. Since the idle rollers are driven by the energy from the strip, they cause tension fluctuations, and as a result it is not difficult to find furnace roll driving systems that drive every roll in the furnace using motors as shown in figure 1. By attaching a motor to every roll, it is possible to obtain high speed operation of over 500 meters per minute (MPM) due to the improved speed control synchronization performance between the roll and strip. Because it is not practical to install measurement sensors in every span, the control systems must cope with the unknown disturbances and delay due to the inability of sensing the feedback signal close to where the signal is controlled. A speed based tension control system is employed for each driven roller within the heating section with an ability to adjust the control system for each roller with information from control systems of other rollers within the zone, as shown in Figure 2.

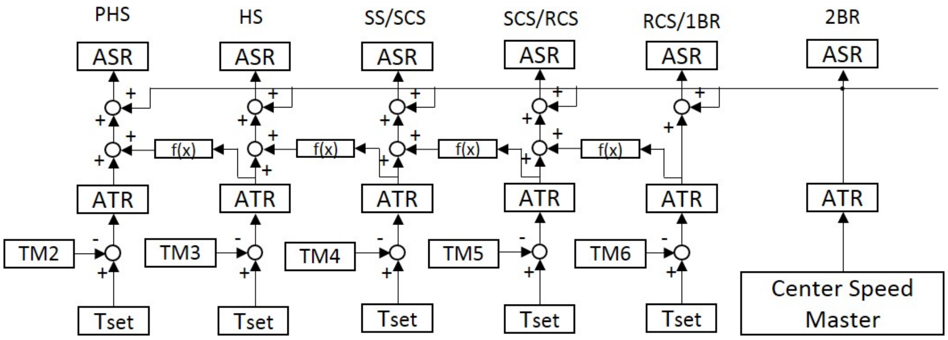

Figure 2 – CGL/CAL Control block diagram

Heating and cooling of strip

In the annealing process, strip heating is necessary to soften the material that is very hard just before its entry into the furnace. To obtain the strip target temperature, direct or indirect heating methods are used. In older facilities, direct heating method that uses direct fire flame was applied. But in continuous annealing lines developed in recent times, indirect heating such as radiant tube heating is employed to obtain high quality surface even with low energy consumption. In the heating section, many heating tubes are packed in between strip and rolls to heat up the strip temperature. Because it is expensive to install many temperature sensors in each strip span of the heating section, only the strip temperature at the exit of the zone is measured by a temperature sensor installed at the exit point. Even though it is possible to estimate the temperature of each span by theoretical heat transfer models based on the type of heat sources used to heat the strip, simplified interpolated temperature calculation will be used in this study for modeling of the temperature distribution and associated thermal strain.

Cooling of the strip in the furnace is critical for adjusting or programming its mechanical properties. To cool the strip, cooling chambers which are also packed in between the strip space are used. Cooling chambers attached with specially designed nozzles injecting cooling agents like HN gas or water mist are typically employed. In this situation also, the strip temperature at specific locations within the furnace can be predicted using theoretical heat transfer models, but interpolated strip temperature based on measured section exit temperature will be used in the models. A typical desired temperature map for the various sections of the annealing furnace is shown in figure 3. Note that the desired strip temperature at the exit of each zone is typically given and indicated by the solid dots in the figure; in this illustration, a linear interpolation is used to join these desired temperature set points. The temperature profile in the steel strip within each zone is highly dependent on the type and location of heating sources within the zone and need not follow the linear profile shown in the temperature map.

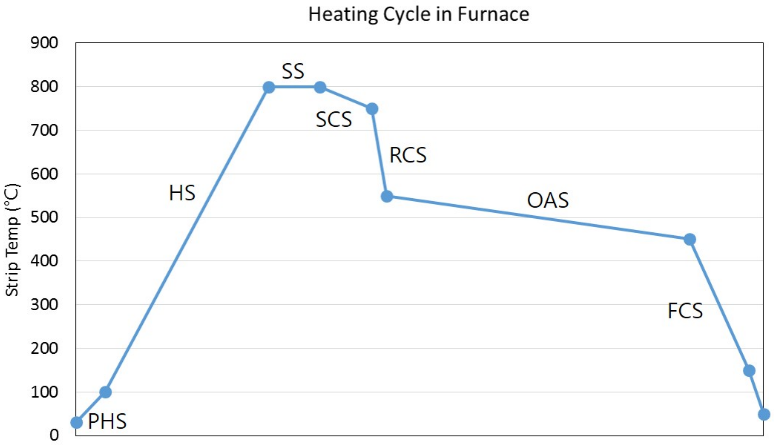

Figure 3 – Temperature Map within Annealing Furnace

Governing equations for strip tension and speed

The governing equation for web tension for materials transported on rollers through roll-to-roll (R2R) process machinery has been developed and refined over several decades by many authors working in specific applications of R2R processing. The key distinction among these related works is the type of material transported through the R2R machine. There have been several modeling investigations that are specific to the metals industry and this study will draw from the results of those investigations towards the development of an adaptive tension controller. In particular, the study will initially consider the methods used in [3] to estimate strip temperature and coefficient of thermal expansion, and subsequently a simple expression used to express modulus of elasticity as a function of strip temperature.

The control volume used in developing the governing equations is shown in figure 4.

In the development of a governing equation for strip strain in a web span between two rollers, conservation of mass in a control volume encompassing the web span is typically employed. This formulation correctly predicts the transport of strain from one span to the next in the transport direction. The resulting governing equation for strain in the i^{th} span is given by

$$\frac{d}{dt}\left[\frac{L_i}{1+\varepsilon_i(t)}\right] = \frac{v_{i-1}}{1+\varepsilon_{i-1}(t)} - \frac{v_i}{1+\varepsilon_i(t)}. \qquad \{1\}$$

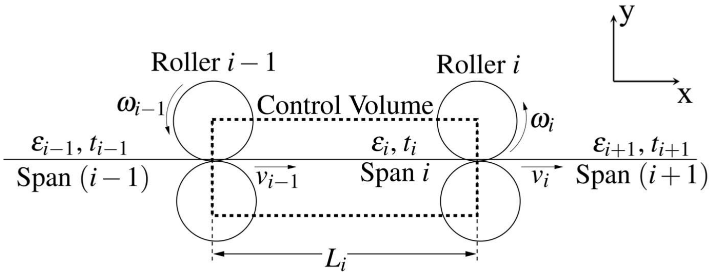

Figure 4 – Span and roller notation for developing governing equations

If small strain is assumed, that is, $1/(1+\varepsilon) \approx (1-\varepsilon)$ which is true for metal webs, then the governing equation for strain is

$$\frac{d\varepsilon_i(t)}{dt} = \frac{1}{L_i}(v_i(t) - v_{i-1}(t)) + \frac{1}{L_i}(v_{i-1}(t)\varepsilon_{i-1}(t) - v_i(t)\varepsilon_i(t)). \quad \{2\}$$

The total strain $\varepsilon_i(t)$ is a combination of mechanical strain (induced by loading) and thermal strain. It is typical to assume that the mechanical strain and thermal strain are independent and the total strain is taken to be the sum of these two strains, that is, $\varepsilon_i(t) = \varepsilon_i^m(t) + \varepsilon_i^\theta(t)$. The mechanical strain is related to tension via a constitutive material law.

Since metal webs are transported in the low strain region, they exhibit linear elastic behavior. It is also assumed that the linear elastic behavior is valid under the elevated temperature of the strip. Therefore, the following linear elastic stress-strain relation is employed:

$$\frac{t_i(t)}{A} = E_i(\theta)\varepsilon_i^m(t). \quad \{3\}$$

The modulus of elasticity $E_i(\theta)$ is a function of the strip temperature. For heating/cooling of the moving strip, the strip temperature is a function of the strip longitudinal position (x). Therefore, subsequent developments will use the expression $E_i(x)$ to indicate that the modulus is a function of the transport direction coordinate. The modulus may be obtained as a function of temperature by conducting tensile tests on steel strip specimens. For example, the modulus as a function of temperature is provided for one type of steel in figure 5. Considering an infinitesimal length of web, using the linear elastic stress-strain relationship, and averaging over the length of the heating or cooling section, the following equivalent modulus may be obtained:

$$E_{i,eq} = \frac{L_i}{\int_0^{L_i} \frac{1}{E_i(x)} dx}. \quad \{4\}$$

The thermal strain is assumed to be a linear function of the strip temperature with a varying coefficient of thermal expansion:

$$\varepsilon_i^\theta = \alpha_i(x)(\theta_i(x) - \theta_0). \quad \{5\}$$

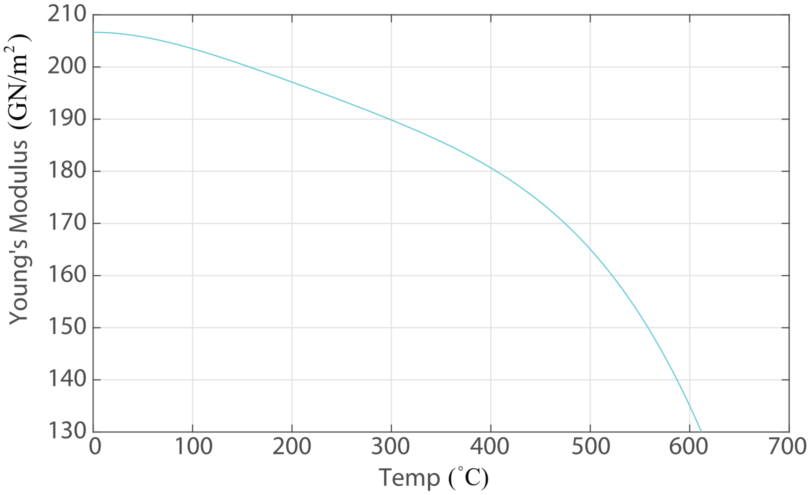

Figure 5 – Strip Young's modulus change with temperature

The equivalent thermal strain along the length of heating or cooling section is an average of the strain for each infinitesimal length dx:

$$\varepsilon^{\theta}_{i,eq} = \frac{1}{L_i}\int_0^{L_i} \varepsilon^{\theta}_i(x)dx. \qquad \{6\}$$

The material constitutive law and equivalent strain and Young's modulus introduced above are used to derive the governing equation for tension from the strain equation {2}. Using the developments {4} and {6} given above, the following is the governing equation for web tension in a heating or cooling section of length L_i:

$$\begin{aligned}\frac{dt_i(t)}{dt} &= \frac{AE_{i,eq}}{L_i}(v_i(t)-v_{i-1}(t)) + \frac{E_{i,eq}}{L_iE_{i-1,eq}}t_{i-1}(t)v_{i-1}(t) - \frac{1}{L_i}t_i(t)v_i(t) \\ &\quad + \frac{AE_{i,eq}\varepsilon^{\theta}_{i-1,eq}}{L_i}v_{i-1}(t) - \frac{AE_{i,eq}\varepsilon^{\theta}_{i,eq}}{L_i}v_i(t). \qquad \{7\}\end{aligned}$$

The governing equation for tension is nonlinear and reflects the transport of strain (both mechanical and thermal) from the upstream span. This equation can be applied to either each strip span or zone. If multiple spans or zones are involved as in the case of the continuous steel strip processing lines, then this equation can be applied sequentially to those spans.

The governing equation for strip transport speed on a roller is typically obtained by assuming that there is no slip between the roller surface and the strip, that is, the peripheral velocity of the roller is equal to strip speed, $v_i = R_i\omega_i$. The governing equation for the angular velocity of the roller is given by

$$J_i\frac{d\omega_i}{dt} = R_i(t_{i+1}(t) - t_i(t)) - B_{fi}\omega_i + K_{mi}\tau_{mi}. \qquad \{8\}$$

Substitution of $v_i = R_i\omega_i$ into the above equation results in the following governing equation for strip transport speed on the i^{th} roller:

$$\frac{dv_i}{dt} = \frac{R_i^2}{J_i}(t_{i+1}(t) - t_i(t)) - \frac{B_{fi}}{J_i}v_i + \frac{K_{mi}R_i}{J_i}\tau_{mi}. \qquad \{9\}$$

For consideration of multiple spans and rollers, strip transport speed on each roller can be obtained by applying the above equation. Note that if slip is significant and cannot be ignored, a slip model, such as the one given in [6], may be used to relate the peripheral speed of the roller and the strip speed.

ADAPTIVE CONTROL DESIGN

In the following, consider control of tension in one zone, that is, a driven roller together with a web span where tension is measured. To simplify the notation in subsequent derivations, define $z_1 = t_i$ and $z_2 = v_i$ for the i^{th} tension zone. Further, the parameters in the tension and speed governing equations are compactly denoted by the following: $c_1 = E_{i,eq}$, $c_2 = \frac{A}{L_i}\left(1 - \varepsilon_{i-1}^{\theta}(L_{i-1})\right)$, $c_3 = \frac{A}{L_i}\left(1 - \varepsilon_i^{\theta}(L_i)\right)$, $c_4 = \frac{E_{i,eq}}{E_{i-1,eq}}$, $c_5 = \frac{R_i^2}{J_i}$, $c_6 = \frac{K_{mi}R_i}{J_i}$, and $c_7 = \frac{Bf_i}{J_i}$. Note that since only one zone is considered, index i is not used on the parameters c_1 through c_7; in subsequent sections for multi-span design, these parameters will be replaced by c_{i1} through c_{i7}. With these definitions, the web tension equation {7} and speed equation {9} are given by

$$\begin{aligned} \dot{z}_1 &= c_1(-c_2 v_{i-1} + c_3 z_2) + c_4\frac{t_{i-1}v_{i-1}}{L_i} - \frac{z_1 z_2}{L_i}, \\ \dot{z}_2 &= c_5(t_{i+1} - z_1) + c_6\tau_{mi} - c_7 z_2. \end{aligned} \qquad \{10\}$$

To simplify the notation in equations, define the nonlinear block controllable expressions $f_1(z_1) = -c_1c_2v_{i-1} + c_4\frac{t_{i-1}v_{i-1}}{L_i}$, $B_1(z_1) = c_1c_3 - \frac{z_1}{L_i}$, $f_2(z_1,z_2) = c_5(t_{i+1} - z_1) - c_7z_2$, and $B_2(z_1,z_2) = c_6$. The objective of the controller is to control z_1 to track a desired tension z_1^d. Four control gains, K_1, K_2, K_3, K_4, are utilized in the following developments. To apply the sliding mode control method, the first sliding surface is defined as the tension error:

$$s_1 = z_1 - z_1^d. \qquad \{11\}$$

The dynamics of s_1 are described by

$$\dot{s}_1 = f_1(z_1) + B_1(z_1)z_2 - \dot{z}_1^d. \qquad \{12\}$$

Considering z_2 as the forcing term for the surface dynamics, then $s_1\dot{s}_1 < 0$ if z_2 reaches z_2^d, and

$$z_2^d = \frac{1}{B_1(z_1)}\left[\dot{z}_1^d - f_1(z_1) - K_1 s_1\right]. \qquad \{13\}$$

Now the next step is to control z_2 to track z_2^d. Define $s_2 = z_2 - z_2^d$ and the same procedure shows that $s_1\dot{s}_1 + s_2\dot{s}_2 < 0$ if the control torque input is

$$\tau_{mi} = \frac{1}{B_2(z_1,z_2)}\left[\dot{z}_2^d - f_2(z_1,z_2) - c_1c_3s_1 + \frac{z_1}{L_i}s_1 - K_2s_2\right]. \qquad \{14\}$$

Note that the parameters c_1 and c_4 are dependent on the elastic modulus. These parameters are not well known since a good method for computing elastic modulus is not available for heated/cooled webs. To account for uncertainties in the elastic modulus, estimation of c_1 and c_4 is considered. Denote the estimates as $\hat{c}_1$ and $\hat{c}_4$, and the adaptive laws are developed as [12]:

$$\begin{aligned} \dot{\hat{c}}_1 &= \frac{\left(-c_2v_{i-1} + c_3z_2^d + c_3s_2\right)s_1}{K_3}, \\ \dot{\hat{c}}_4 &= \frac{t_{i-1}v_{i-1}s_1}{K_4L_i}, \end{aligned} \qquad \{15\}$$

This adaptive control algorithm based on dual loop control method is illustrated in Figure 6.

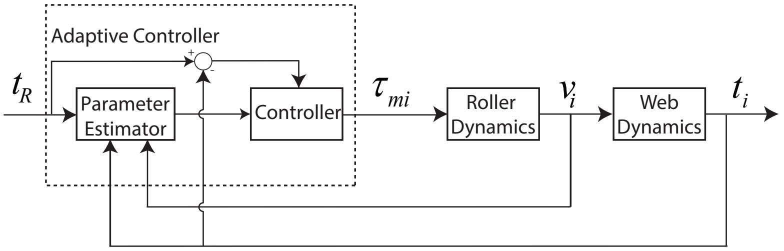

Figure 6 – Adaptive tension control strategy

In a steel strip processing line, strip tension is measured between heating/cooling sections and there is no measurement of tension in spans within a heating or cooling section. Therefore, an observer that can estimate tension in spans where it is not measured would be of value in controlling tension more precisely in spans within a heating or cooling section. A model based observer is derived in the following to estimate tension.

Tension observer design

The procedure for designing a model-based observer is illustrated with a single span (i^{th} span). It is assumed that the tension in the $(i-1)^{th}$ and $(i+1)^{th}$ spans is measured. Later in the report this observer will be extended to the multiple span case where the entry and exit tensions into the multiple-span sections are measured.

The following parametric model is considered: $c_{i1} = p_1\bar{c}_{i1}$. To simplify the notation, define the followings: $y = v_i$, $z = t_i$, $f_1(y,z) = c_{i5}(t_{i+1} - z) + c_{i6}\tau_{mi} - c_{i7}y$, $f_2(y,z) = -\frac{yz}{L_i}$, $\phi(y)^T = \begin{bmatrix} -\bar{c}_{i1}c_{i2}v_{i-1} + \bar{c}_{i1}c_{i3}y & \frac{t_{i-1}v_{i-1}}{L_i} \end{bmatrix}$, and $p = \begin{bmatrix} p_1 \\ c_{i4} \end{bmatrix}$ In the above definitions, y is used to denote the measured strip speed, z is the tension that needs to be estimated, τ_{mi} is the motor input, and p is the unknown parameter vector which reflects changes in elastic modulus with temperature. The other three terms, $f_1(y,z)$, $f_2(y,z)$ and $\phi(y)$ are defined such that they facilitate derivation of the observer. Let $\hat{p}(t)$ be the estimate of p, The observer equations are given by

$$\dot{\xi} = -\frac{y\hat{z}}{L_i} + l f_1(\hat{z}) + \phi(y)^T \hat{p}, \qquad \{16\}$$

$$\hat{z} = \xi - ly \qquad \{17\}$$

One possible adaptation algorithm for $\hat{p}(t)$ is given as

$$\dot{\hat{\sigma}} = \Gamma \frac{1}{c_{i5}} \left[\begin{array}{c} c_{i3}y - c_{i2}v_r \\ \frac{t_r v_r}{L_i} \end{array} \right] f_1(y,\hat{z}), \qquad \{18a\}$$

$$\hat{p} = \hat{\sigma} - \frac{\Gamma}{c_{i5}} \left[\begin{array}{c} \frac{c_{i3}}{2}y^2 - c_{i2}v_r y \\ \frac{t_r v_r}{L_i} y \end{array} \right] \qquad \{18b\}$$

where $\Gamma > 0$ is the adaptation gain. Equation {18} provides a parameter estimation algorithm where the derivative of the estimate depends on the measured output only.

MODEL SIMULATIONS

Model simulations are useful in understanding the behavior of the strip and for the development of the controller prior to conducting experimental studies. A program in MATLAB/Simulink was developed and simulation parameters that mimic the real plant operation are considered as given in Table 1. In heating sections of continuous annealing lines, the strip temperature is raised up to 800 °C in order to soften the material. To raise the strip temperature, heating devices are installed in a furnace that provides an insulated controlled heating environment. For the effective heating, a heating device is installed in each strip span. By applying the same amount of heat from each heating device, the strip temperature rises gradually as it passes through the spans of the heating section so that the heat transfer appears in the form of sum of each span temperature as the web is transported from one span to another span up to the exit of the section. The temperature in each span in this heating and temperature adding process is shown in Figure 7. In this simulation, strip temperature rises by 30 °C as it passes through each roll span. The total temperature rise after passing through five spans is 150 °C, so that the exit span temperature would be 650 °C.

In modern continuous strip processing lines, all transport (helper) rolls are driven by electric motors. As the first step of the multi-span model simulation, speed control is simulated by applying the speed control input to each of these helper rolls. After some PI gain tuning for speed control loop, strip web transport process during temperature transient from 500 to 650 °C was

Parameter	Value
Strip thickness	0.7 mm
Strip width	1500 mm
Strip span length	20 m
Line speed	300 mpm
Strip temperature	500 ~ 800 °C

Table 1 – Simulation parameters

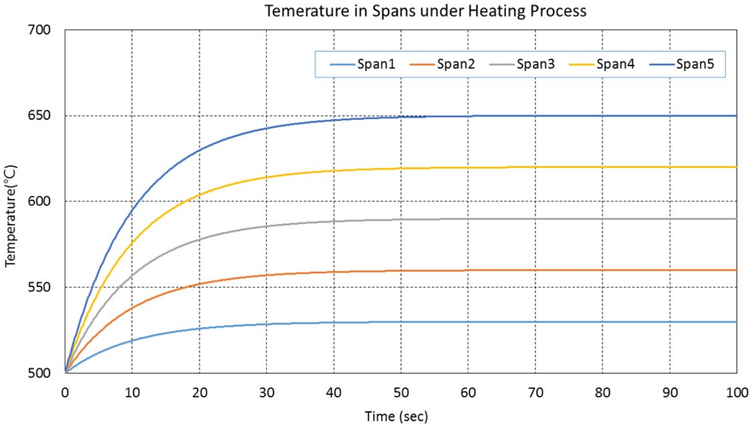

Figure 7 – Temperature profile of each span in heating section

simulated. Web speed on each roll is controlled to within 0.001 m/s of the reference speed of 5.0 m/s. Speed control for each roll provides swift compensation speed feedback. Instead of obtaining perfect speed control performance, tension response in each span is loosened up to 730 kgf for the reference tension of 1000 kgf (Figure 8). Because there is no compensation for the strip strain due to the thermal transient which results in tension not following the reference value in the heating section spans.

In cooling sections of continuous annealing lines, the strip temperature cools down from 800 °C to 100 °C when passing through two separate sections in order to adjust its material properties. To cool down the strip temperature, cooling devices are installed in the furnace under insulated controlled cooling environment. To obtain effective cooling, a cooling device is installed in each strip span. By removing some amount of heat with each cooling device, the strip temperature is decreased gradually as it passes through the entire cooling section so that the total heat removed appears in the form of sum of each span temperature down to the exit of the section. The temperature in each span in this cooling and temperature down process is shown in Figure 9. In this simulation, strip temperature cools down by 30 °C as it passes through each roll

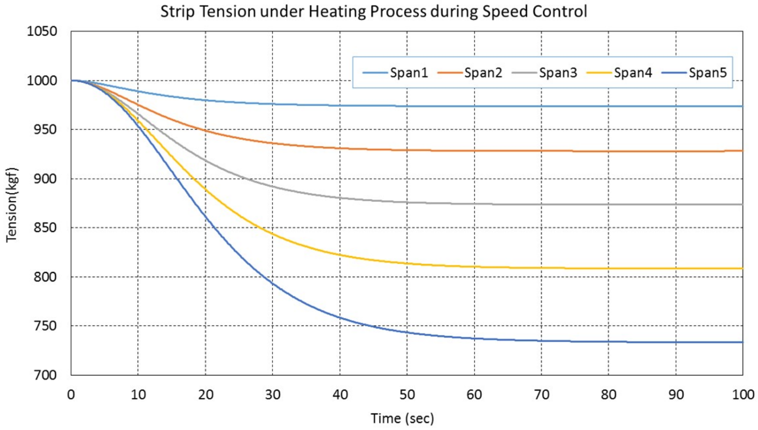

Figure 8 – Tension profile of each span in heating section

span. The total temperature decrease in the strip after passing through five spans is 150 °C, so that exit temperature would be 350 °C. And during this cooling process, the tension simulation results are shown in Figure 10.

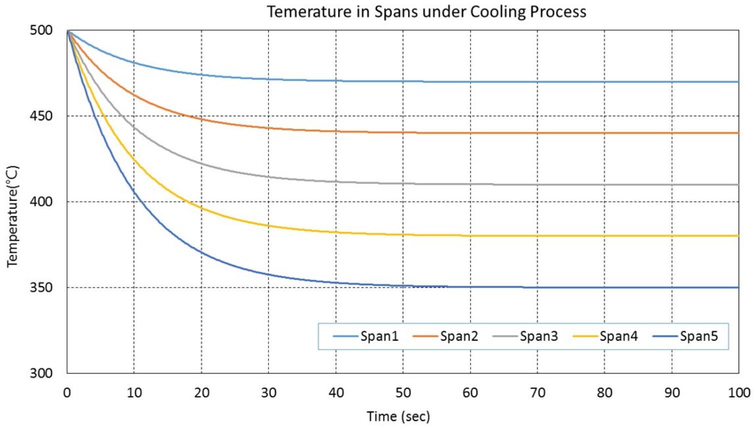

Figure 9 – Temperature profile of each span in cooling section

The controller and observer discussed in aforementioned sections are simulated in MATLAB/Simulink for a section of multi-span strips. The tension in the target spans are not measured but only the tension in the entry and exit spans are measured. The implementation of the tension controller uses the tension estimate from the observer. The inner speed-loop is based on measured speed and the outer-tension loop is based on the estimate from the observer.

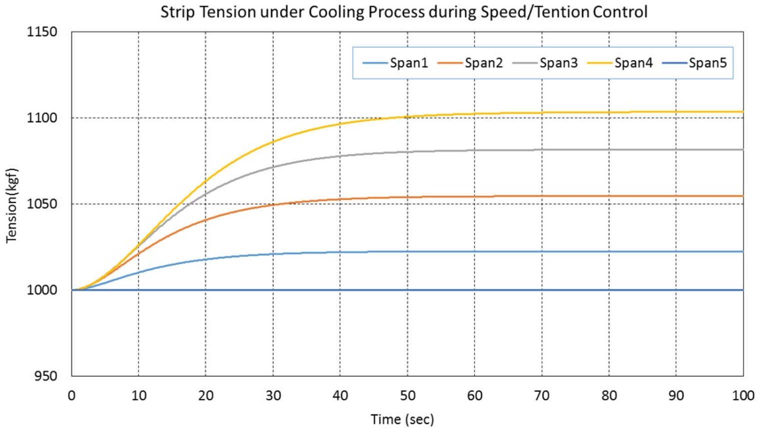

Figure 10 – Tension profile of each span in cooling section

Multi-span strips with known time -varying parameters case observer with PID controller is presented and 5 spans are simulated. The simulation results are shown in Figures 11, 12, and 13. The initial values of tension in spans 1 through 4 are 980 kgf, 940 kgf, 880 kgf, and 810 kgf. The initial estimates of tension in the observer were taken to be equal to the reference tension which is 1000 kgf. The time-varying modulus for different spans is shown in Figure 14.

CONCLUSION

In this paper modeling and tension control of a steel strip transported through heating/cooling sections of a continuous galvanizing/annealing line was investigated. Temperature effects were included in the model to reflect the changing temperature on strip tension in heating and cooling sections. An adaptive sliding mode controller is designed for regulated strip speed and tension in spans where tension measurement is available. A nonlinear model-based tension observer is developed to estimate tension in heating/cooling spans where tension measurement is not available. Current practice is to control strip speed using helper rolls in these sections. Strip tension is controlled in only those spans of the heating/cooling section of the line where tension measurement is available. By estimating tension using a tension observer one can use estimated tension feedback for helper rolls to better regulate tension within the heating/cooling spans. Extensive model simulations with various scenarios were conducted to illustrate the methods developed in controlling tension in heating/cooling spans where tension measurement is unavailable.

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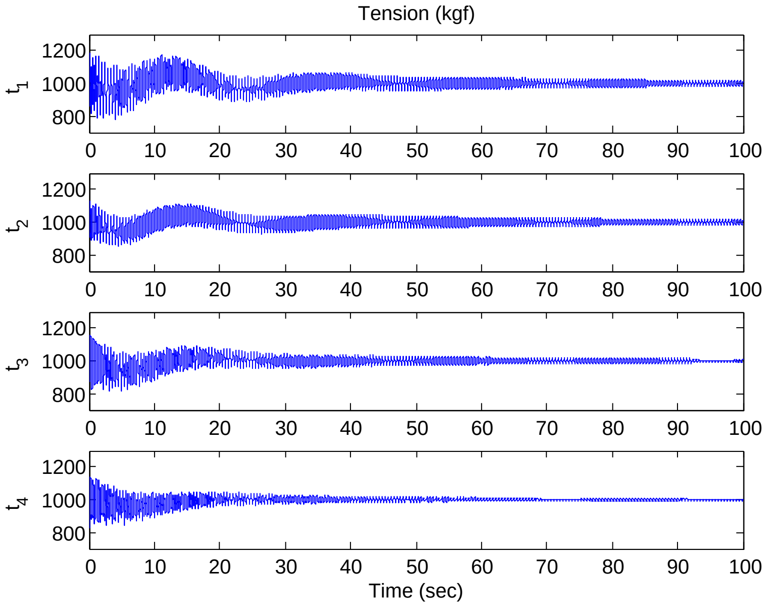

Figure 11 – Tension response of multi-span with controller and observer

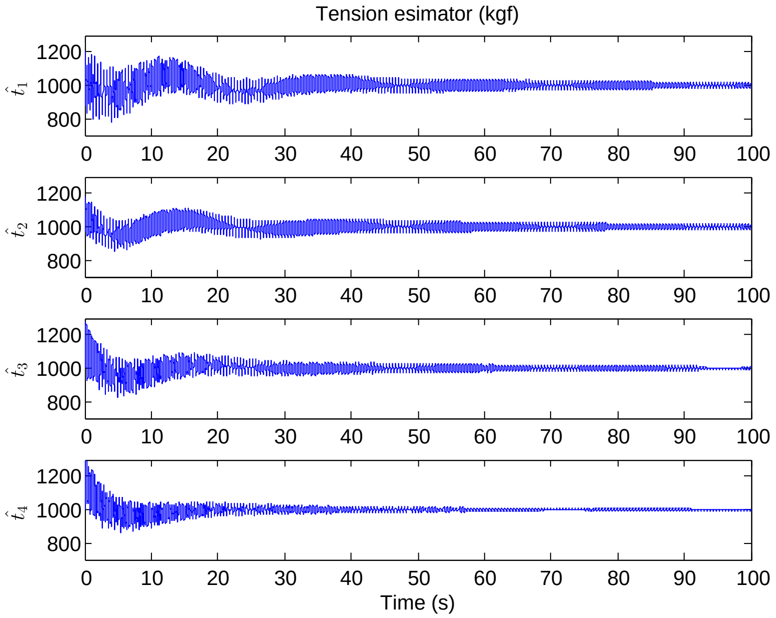

Figure 12 – Tension estimate response of multi-span with controller and observer

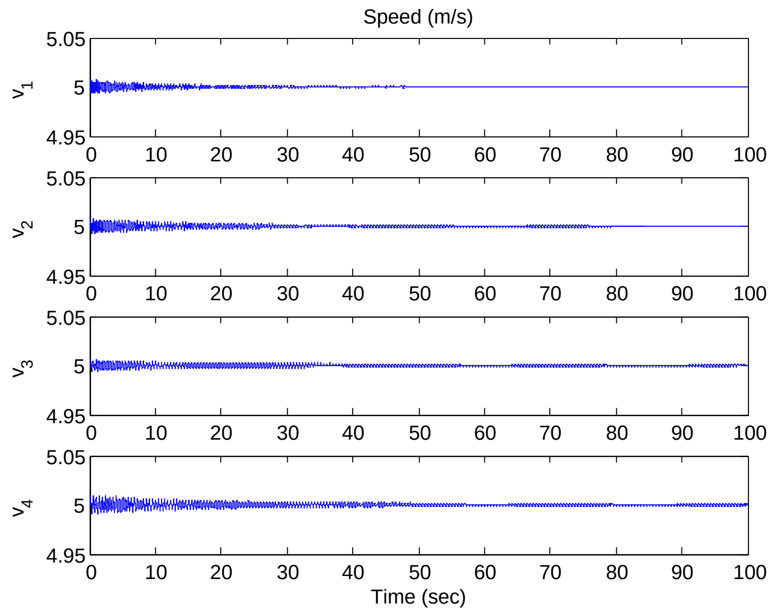

Figure 13 – Speed response of multi-span with controller and observer

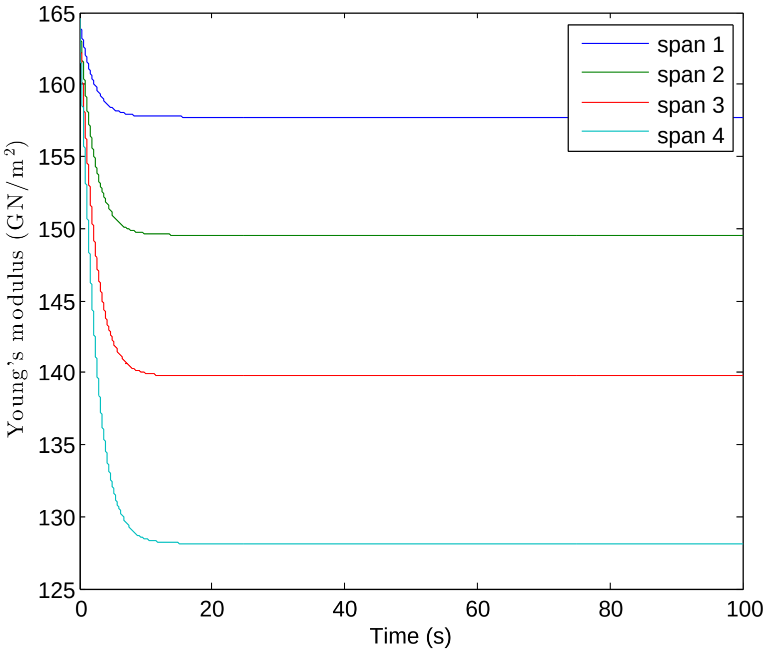

Figure 14 – Modulus in different spans of multi-span with controller and observer