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Real-Time Tension Control in a Multi-Stand Rolling System

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The problem of real-time tension control in a metal-strip processing line is addressed. The tension in a metal strip changes due to not only the speed difference but also thickness changes at the ends of a span. The mathematical dynamic model which describes relationship between the tension change and the roll-speed change is improved to include the effect of the strip thickness change on tension variation. Through the computer simulation of this model, the parameter sensitivity analysis and the static and dynamic characteristic study are carried out. The tension variation in a metal strip turned out to be very sensitive to the thickness variation as well as to the speed difference at the ends of the metal strip. In the rolling process, the master speed drive is usually located at the last stand. The speeds of rollers in upstream stands are adjusted with respect to the speed of the last stand to compensate the speed change for the tension regulation. A new tension control strategy in a multi-stand rolling process is suggested. The tension transfer phenomena is used in the design of the suggested controller. The developed mathematical model is used to design a controller for the real-time control system. A set of requirements for the real-time tension control is suggested. Based on the requirements, a real-time software for the tension control in a multi-stand system is designed and real-time simulation was carried out by using the VxWorks real-time scheduler and the Force Target board. The cancellation mechanism of the roll gap control due to the tension interaction is clearly defined by using the mathematical model derived in this study. It is confirmed that the suggested control strategy needs less control efforts and shows better performance than those of the existing control method in a rolling process.

Key Words : Rolling System, Tension Control, Tension Transfer, Real-Time System, Mathematical Model, Automatic Gauge Control

Nomenclature

A : Cross-sectional area of strip
E : Modulus of elasticity
L : Length of strip span
h_{i0} : Steady-state value of strip thickness
H_i : Change in strip thickness from a steady-state operating value
h_i : Strip thickness $(=h_{i0}+H_i)$
Ks : Equivalent stand spring constant
p : Rolling force
P_i : Change in rolling force from a steady-state operating value
R : Radius of roll or roller
S : Change in roll gap from a steady-state operating value
t_{i0} : Steady-state value of strip tension
T_i : Change in strip tension from a steady-state operating value
t_i : Strip tension $(=t_{i0}+T_i)$
U : Control value
v_{i0} : Steady-state operating value of strip speed
V_i : Change in strip speed from a steady-state operating value
v_i : Strip speed $(=v_{i0}+V_i)$
ε : Strain of metal strip

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Subscripts:

0 : Steady-state operating condition

i : 1, 2, 3, 4 ...

1. Introduction

The automatic gauge control (AGC) system in a metal strip rolling system process generally consists of the three major control systems: a roll gap control, a roll speed control, and a strip tension control system. These control systems heavily interact each other(Vladimir, 1993). The thickness of the strip can be changed by using the roll gap, but can not be controlled precisely without controlling the tension of the strip. The tension in a strip can be again changed by speeds and thickness at the ends of a strip. It is also reported that the effect of roll gap control can be cancelled out due to the interaction between the strip tension and roll gap. But, authors could not find literature on the mathematical model that fully describes interactions among the roll gap, the roll speed, and the strip tension. In order to design a highly accurate AGC system, a better mathematical model is necessary.

Grimble(1976) derived a mathematical model which describes the relationship between the strip tension and the roll speed in a single span. He studied the effects of the parameter changes and the undriven rolls on tension variation using his mathematical model. From his mathematical model though, it is impossible to predict the tension transfer and the tension variation due to the thickness change at the ends of a strip.

The minimum tension control(MTC) method was developed by Siemens in Germany (Bass, 1987). In MTC method, the strip tension is calculated from the change in rolling torque in a stand before and after the strip enters the following stand. The method of successive set point coordination of speeds is used to control the strip tension with the MTC loop superimposed. It is difficult to determine the strip tension accurately since the change in rolling torque due to tension variation is very small in value compared with the operating torque value. Moreover, there is no way to determine the tension variation after the strip is nipped at both ends of the strip.

In this paper, a new mathematical model which describes the relationship among the roll gap, the roll speed, and the strip tension is developed. Through the computer simulation, characteristics of tension variation due to the change in roll gap and speed are studied. The tension variation in a metal strip turned out to be very sensitive to the thickness variation as well as to the speed difference at the ends of the metal strip. The cancellation mechanism of roll gap control due to the tension interaction is also shown by using this model.

In the industrial rolling process, the master speed drive(MSD) is usually located at the last stand. The speeds of rolls in upstream stands are adjusted with respect to the speed of the last stand to compensate the speed change for the tension regulation. A new tension control strategy in a multi-stand rolling process is suggested. In the suggested control strategy, the MSD is located in the first stand(or upstream stand) and the tension transfer phenomena is used. The suggested control strategy needs less control efforts and shows better performance than those of the existing control method in a rolling process.

The developed mathematical model is used to design a controller for the real-time control system. A real-time software for the tension control in a multi-stand system is designed by using the VxWorks real-time scheduler and the Force Target board.

2. Strip Tension, Roll Speed, and Strip Thickness Relationship

Consider a metal strip with tension between two stands as shown in Fig. 1.

In the Fig. 1, the strip is transported from left to right and rolled to change its thickness from h_0 to h_1 and h_2, consecutively. The machine-direction strain of the metal strip is ε_0 in the entrance side of stand #1, ε_1 between stand #1 and stand #2, and ε_2 in the exit side of the stand #2. In order to facilitate the derivation of the mathematical model for tension, the rolling process is divided

Table 1 Tension variations due to change in speed and thickness.

	T_1(MN)	T_2(MN)
$H_1(-5\%)$	1.104	0.581
$H_2(-5\%)$	−1.102	0.212
$H_3(-5\%)$	0.000	−0.375
$V_1(5\%)$	−1.102	−0.551
$V_2(5\%)$	1.102	−0.184
$V_3(5\%)$	0.000	0.775

(The values of operating conition: $h_{10}=2.4$, $h_{20}=1.8$, $h_{30}=1.2$ mm, $v_{10}=3000$, $v_{20}=4000$, $v_{30}=6000$ mm/s)

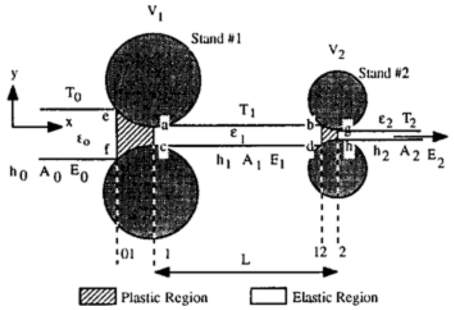

Fig. 1 Rolling of a Strip with Tension between Two Stands.

into the plastic (01-1, 12-2 region) and the elastic region (1-12 region) as shown in Fig. 1. It is assumed that the strip thickness at the neutral point (where the strip speed and the tangential speed of the roll are same: 1 and 2 in Fig. 1) is equal to the thickness at the exit side of the stand.

For the plastic and the elastic regions in Fig. 1, the law of conservation of mass, stress-strain relationship, and Hooke's law are used to derive a mathematical model which describes a dynamic relationship among the strip tension, the roll speed, and the strip thickness as follows (Shin et. al., 1993):

$$\frac{d}{dt}[T_1(t)]=-\frac{v_{20}}{L}T_1(t)+\frac{v_{10}}{L}\frac{A_1E_1}{A_0E_0}T_0(t)+\frac{A_1E_1}{L}\left[\frac{v_2h_{20}+v_{20}H_2-v_{120}H_1}{h_{10}}-V_1(t)\right] \quad (1)$$

Equation (1) shows that the tension in a strip between two stands is very sensitive not only to the speed changes but also to the thickness changes of strip at the ends of the strip.

The tension variation due to changes in speed and thickness are calculated using the mathematical model. The results are shown in the Table 1. Note that more variation in speed or thickness than 7% of the steady-state values may cause a plastic elongation, which may induce a necking in the strip.

3. Cancellation of Roll Gap Control Due to Tension Interaction

When the strip at the exit side is thicker than desired, the AGC will reduce the roll gap resulting in lower entry strip tension. Consequently, when the entry strip tension reduces, the exit strip thickness increases, canceling the effect of AGC (Vladimir, 1993). No literature which has reported this cancellation mechanism is available. This cancellation mechanism can be shown based on the developed mathematical model together with equations for the rolling process and the rolling force.

The rolling process can be represented by using the gauge meter principle (Gerald, 1990) as follows:

$$H_2=S_2+\frac{P_2}{Ks_2} \quad (2)$$

The change in the rolling force can be calculated by using a linearized version of the Bland and Ford equation for the rolling force (Bland and Ford, 1948).

$$P_2=\frac{\partial p_2}{\partial t_1}T_1+\frac{\partial p_2}{\partial t_2}T_2+\frac{\partial p_2}{\partial h_1}H_1+\frac{\partial p_2}{\partial h_2}H_2 \quad (3)$$

Equations (1) ~ (3) can be solved simultaneously to calculate the strip thickness and the strip tension for the given roll gap and roll speeds. The roll gap and the roll speed were assumed to be controlled perfectly. The simulation results are shown in Figs. 2 and 3. The parameters used for the simulation are shown in Table 2. The roll gap is reduced by 1 % of the operating roll gap ($S_2=1.1189$ mm) to obtain a desired thickness reduction (about 9.5 μm) in the strip at the exit side of the last stand. But, the reduction in the roll gap

Table 2 Parameter values for roll gap control simulation.

Parameter	Value
h_{10}	1.626 mm
h_{20}	1.245 mm
S_2	1.1189 mm
t_{10}	6972 N
t_{20}	7493 N

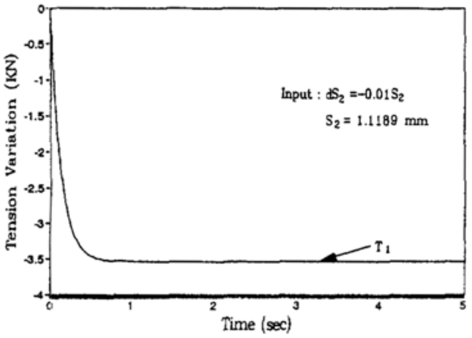

Fig. 2 Tension variation for roll gap change.

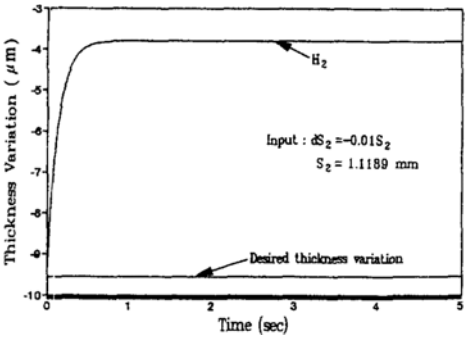

Fig. 3 Strip thickness variation for roll gap change.

(S_2) introduces the reduction in tension (see Eqs. (1), (2), and Fig. 2), and the reduction in the tension (T_1) causes increase in the rolling force (see Eq. (3)). The increase in the rolling force causes the increase in the thickness (see Eq. (2)) which reduces the effect of roll gap control. As shown in Fig. 3, the strip thickness is not controlled as desired (about 60 % error).

4. Tension Control Strategy in Multi-Stand Systems

In many industrial multi-stand rolling systems, the MSD is usually located at the last stand. Upstream roll speeds are correspondingly adjusted to keep the strip tension unchanged in upstream spans even with the roll gap changed in the last stand (MSD) to avoid the cancelling effect of AGC. However, the strip tensions in upstream spans may not be kept unchanged due to the tension transfer phenomena even though the speeds are adjusted (Shin, 1991). The proper selection of the location of the MSD is important for the precise control of the tension and the thickness of the strip.

Consider a multi-stand rolling system shown in Fig. 4 as an example. When the MSD is in location (B), V_3 should be changed to control T_3. And V_2 and V_1 are changed accordingly to compensate the tension variation due to change in V_3. This approach is called as the successive control (or progressive set-point coordination control). The MSD might be located in the last stand since the control of final thickness of the strip at the exit side of the last stand is very important. As pointed out in the previous section, the control of strip tension is very important for the precise control of the strip thickness. And it is not desirable to locate the MSD in the downstream for the good control of tension since tension is transferred from an upstream span to downstream spans.

In this section, the successive control which is commonly used in the industry will be examined. Also, a tension control strategy for multi-stand rolling systems will be suggested which utilizes the tension transfer mechanism.

4.1 Successive control

The mathematical model for tension T_i (i = 1, 2, 3) in the system shown in Fig. 4 can be written as Eqs. (4), (5) and (6) (Shin and Hong, 1994). The effect of thickness change on tension variation will be dropped from this point to simplify the demonstration of a tension control idea to be suggested.

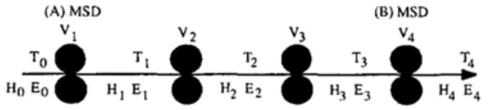

Fig. 4 A Multi-stand rolling system.

$$\frac{dT_1}{dt}=-\frac{v_{20}}{L_1}T_1+\frac{v_{10}}{L_1}\frac{A_1E_1}{A_0E_0}T_0+\frac{A_1E_1}{L_1}(V_2-V_1) \tag{4}$$

$$\frac{dT_2}{dt}=-\frac{v_{30}}{L_2}T_2+\frac{v_{20}}{L_2}\frac{A_2E_2}{A_3E_3}T_1+\frac{A_2E_2}{L_2} \tag{5}$$

$$\frac{dT_3}{dt}=-\frac{v_{40}}{L_3}T_3+\frac{v_{30}}{L_3}T_3+\frac{v_{30}}{L_3}\frac{A_3E_3}{A_2E_2}T_2+\frac{A_3E_3}{L_3}(V_4-V_3) \tag{6}$$

Observing Eqs. (4), (5) and (6), the strip tension Ti can be controlled by the speed difference at the ends of a metal strip (i.e., $V_{i+1}-V_i$). As can be seen in Eqs. (4) and (5), the change in V_2 will vary both T_1 and T_2. The idea of successive control is as follows. Assume that the MSD is in the location (A) of Fig. 4. When V_2 is changed to control T_1, V_3 and V_4 should be changed accordingly to compensate the tension variations in down streams due to speed change in upstream (V_2) in the successive control. But actually, $T_2(\infty)$ will approch $T_2(0)$ in steady state without adjustments in V_3 and V_4 which is clear in Eqs. from (4) to (6). That is, tension variation T_1 due to change in V_2 is transferred to downstreams, which is called as "tension transfer" (Shin, 1991).

In other words, the successive control is based on the following mathematical model, which does not include the "tension transfer" term instead of the model described by Eqs. (4), (5) and (6).

$$\frac{dT_1}{dt}=-\frac{v_{20}}{L_1}T_1+\frac{A_1E_1}{L_1}(V_2-V_1) \tag{7}$$

$$\frac{dT_2}{dt}=-\frac{v_{30}}{L_2}T_2+\frac{A_2E_2}{L_2}(V_3-V_2) \tag{8}$$

$$\frac{dT_3}{dt}=-\frac{v_{40}}{L_3}T_3+\frac{A_3E_3}{L_3}(V_4-V_3) \tag{9}$$

Since Eqs. from (7) to (9) do not fully describe the system, the successive control strategy would not work properly.

4.2 Multi-stand tension control strategy using tension transfer

The mathematical model described by Eqs. (4) ~ (6), clearly shows that strip tension T_i depends on not only the speed difference at the ends of a strip but also on the tension T_{i-1} in an upstream strip. Thus, when V_2 is changed to control T_1 with the MSD in the location (A) of Fig. 4, T_2 and T_3 does not actually vary much even though V_3 and V_4 are not changed successively. If V_3 and V_4 are changed successively, they will become disturbances on T_2 and T_3.

An idea to be suggested is to use the tension transfer mechanism and not to change the speeds successively for the tension control in multi-stand systems.

4.3 Tension control and MSD location

When the MSD is located in a downstream stand, the tension transfer mechanism can not be used in the tension control since tension is transferred from upstream to downstream. It is required to use successive coordination of speed control, which is susceptible to disturbances (speed or thickness). This approach (MSD in downstream stand and successive control) needs extra control effort compared with the suggested idea and will generate undesirable transient performance. Considering the tension transfer and MSD location, a simple and effective tension control strategy is to locate the MSD in the upstream of the strip and use the tension transfer mechanism together with speed adjustment.

4.4 Tension control strategy suggested

An idea that authors want to suggest is to locate the MSD in an upstream stand rather than in downstream stand (or last stand) and to use the phenomenon of tension transfer for the control of tension in the multi-stand rolling systems. Then, speeds of rolls in downstream stands need not adjusted with respect to the speed of the master drive to compensate the speed change for the tension regulation. Examples will be solved later in this paper to demonstrate the advantages of the suggested strategy compared with the method that is commonly used in the industries today (progres-

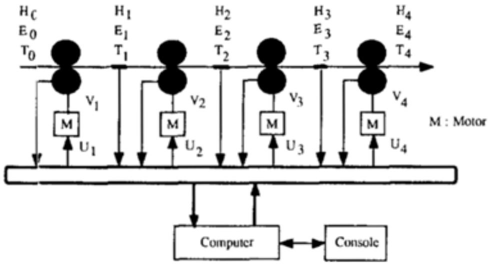

Fig. 5 Real-time system for strip tension control.

sive set point coordination control with MSD in the last stand). Before the comparison of the methods, a real-time tension control system will be designed in the following section.

5. Design of Real-Time Software for Tension Control

A real-time software for tension control in a multi-stand rolling system is designed in this section. Consider a real-time tension control system shown in Fig. 5. It is assumed that there is no slip between the strip and the roll. The strip tension is controlled by using the speed difference between the stands at the ends of a metal strip. The mathematical model was used for the simulation instead of a real system. It was assumed that the tension could be measured exactly.

5.1 Specifications and requirements for real-time software

Important specifications and requirements include followings. The mathematical model for tension and speed of the system should be activated periodically with the interval of the sampling period (Puscher and Koza, 1989). The mathematical model task for speed and tension and the control task should be synchronized. While a task uses a global data, the data should be mutually excluded so that other tasks can not use the data. The periods of the periodic tasks should be kept consistently. The values of the state variables should be logged in the file periodically.

5.2 Tasking

In order to satisfy the specifications and the requirements, tasking was carried out as follows.

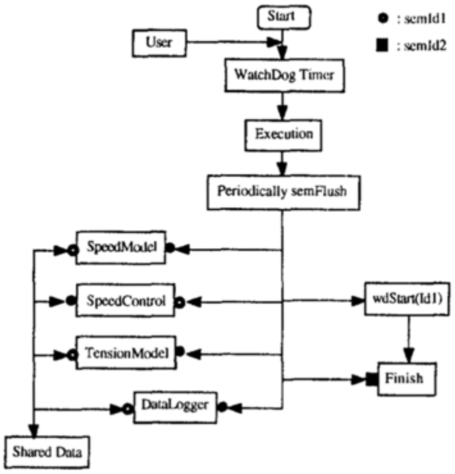

Fig. 6 Behavioral requirements of tasks.

speedModel( )
speedControl( )
tensionModel( )
dataLogger( )
finish( )

The tasks are listed in the order of priority (higher priority task first). The behavioral requirements between tasks are shown in Fig. 6. The program begins with the execution of the start( ) function which initializes real time functions and timers, creates tasks and semaphores, opens files to be used, obtains parameter values from user, sets the system clock.

5.3 Time scheduling for periodic tasks

In order to guarantee the timing of the periodic tasks, the execution time of tasks were measured by using the tickSet( ) and tickGet( ) functions. The watchDog timer was used to generate the semaphore periodically such that execution activation periods of the periodic tasks can be met as planned.

6. Real-Time Simulation

For the real-time simulation, the following tension control system and the mathematical model were used. To demonstrate the advantages of the suggested control strategy, two cases of the tension control system were simulated and the

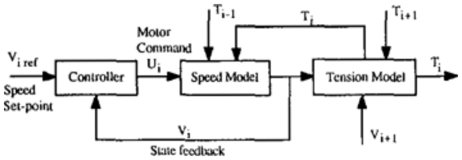

Fig. 7 A Block diagram of the tension control system.

results were compared.

(A) When the MSD is located at the first stand of the system shown in Fig. 4.

(B) When the MSD is located at the last stand.

6.1 Tension control system

A block diagram of the tension control system is shown in Fig. 7. The mathematical model for the speed of roller can be written in Eqs. from (10) to (12) by applying the torque balance to the rollers.

$$\frac{dV_2}{dt}=\frac{B_{f2}}{J_2}V_2+R_2^2(T_2-T_1)+\frac{R_2}{J_2}K_2U_2 \tag{10}$$

$$\frac{dV_3}{dt}=\frac{B_{f3}}{J_3}V_3+R_3^2(T_3-T_2)+\frac{R_3}{J_3}K_3U_3 \tag{11}$$

$$\frac{dV_4}{dt}=\frac{B_{f4}}{J_4}V_4+R_4^2(T_4-T_3)+\frac{R_4}{J_4}K_4U_4 \tag{12}$$

Table 3 Parameter values for real-time simulation.

Parameter		Value
E_0 E_1 E_2 E_3	Yung's modulus	2.450 N/mm^2
L_1 L_2 L_3	Span Lengh	1,000 mm
R_1 R_2 R_3 R_4	Roll Radius	150 mm
J_1 J_2 J_3 J_4	Mass moment of inertia	237×103 $kgmm^2$
Bf_1 Bf_2 Bf_3 Bf_4	Fricition Coefficient	0.2
C_1 C_2 C_3 C_4	Motor Torque/Speed contstant	0.01
K_1 K_2 K_3 K_4	Motor torque contstant	12×10^6
A_0	Cross sectional area	3,000 mm^2
A_1	Cross sectional area	2,500 mm^2
A_2	Cross sectional area	2,000 mm^2
A_3	Cross sectional area	1,500 mm^2
A_4	Cross sectional area	1,000 mm^2
V_{10}	Strip exit speed	2,400 mm/s
V_{20}	Strip exit speed	3,000 mm/s
V_{30}	Strip exit speed	4,000 mm/s
V_{40}	Strip exit speed	6,000 mm/s
h_0	Strip thickness	3.0 mm
h_{10}	Strip thickness	2.5 mm
h_{20}	Strip thickness	2.0 mm
h_{30}	Strip thickness	1.5 mm
h_{40}	Strip thickness	1.0 mm

The speed of the roll is controlled in a closed loop. But, the strip tension is controlled in an open loop in order to simply show advantages of the suggested control strategy. The mathematical model represented as in Eqs. from (4) to (6) and from (10) to (12) was descretized with sampling period 0.01 second as follows.

Tension model:

$$\begin{aligned} T_1(k+1) &= 0.9704\ T_1(k) + 48.2723\ V_2(k) \\ T_2(k+1) &= 0.0232\ T_1(k) + 0.9608\ T_2(k) \\ &\quad - 47.1845\ V_2(k) + 36.0247\ V_3(k) \\ T_3(k+1) &= 0.0003\ T_1(k) + 0.0285\ T_2(k) \\ &\quad + 0.9418\ T_3(k) - 0.7052\ V_2(k) \\ &\quad - 35.1360\ V_3(k) + 23.7795\ V_4(k) \end{aligned} \tag{13}$$

Speed model:

$$\begin{aligned} V_2(k+1) &= 1.000\ V_2(k) - 0.9810\ T_1(k) \\ &\quad + 0.9810\ T_2(k) + 74.48\ U_2(k) \\ V_3(k+1) &= 1.000\ V_3(k) - 0.9810\ T_2(k) \\ &\quad + 0.9810\ T_3(k) + 74.48\ U_3(k) \\ V_4(k+1) &= 1.000\ V_4(k) - 0.9810\ T_3(k) \\ &\quad + 74.48\ U_4(k) \end{aligned} \tag{14}$$

The control for the speed was designed such that the desired poles are located at 0.35 (Ogata, 1990).

$$\begin{aligned} U_2(k) &= -0.0083(V_{2ref} - V_2(k)) \\ U_3(k) &= -0.0083(V_{3ref} - V_3(k)) \\ U_4(k) &= -0.0083(V_{4ref} - V_4(k)) \end{aligned} \tag{15}$$

The parameter values for the real-time system simulation are shown in Table 3.

6.2 Computer simulations and results

Tension variations at the entrance of the first stand and the exit side of the last stand are assumed to be zero. The reference step input to the speed model was selected as 1% of the operating speed.

(A) With MSD at the first stand: the control objective is to keep $T_1(\infty) = 48$, $T_2(\infty) = T_3(\infty) = 0$.

(1) A speed change only in the V_2 is allowed to achieve the tension control objective without successive coordination of speed in downstream stand. The tension variation for given change in speed, V_2, is shown in the Fig. 8. Tensions T_1, T_2, and T_3 were controlled as desired even though there is small steady state and transient error.

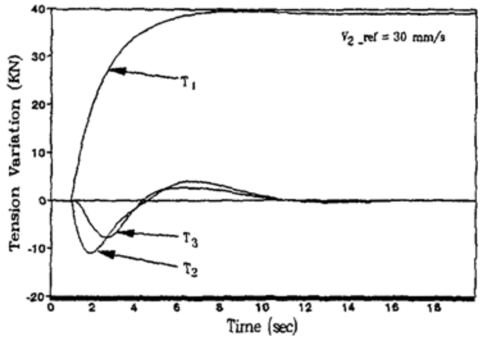

Fig. 8 Tension control without successive control: MSD at first stand.

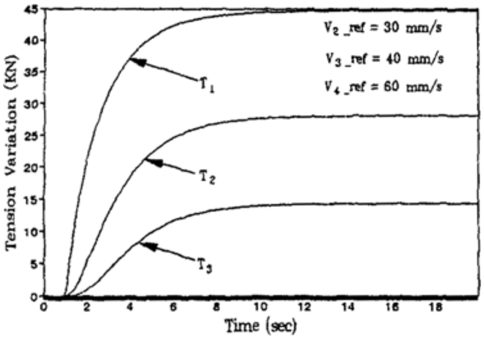

Fig. 9 Tension control with successive control: MSD at first stand.

(2) A speed change in the V_2 is adjusted to achieve the tension control objective. And the speed of the downstream roll is adjusted accordingly to compensate the speed change in the V_2: progressive set-point coordination control. The simulation results are shown in Fig. 9. Tension T_1 was controlled with small steady state error, but the T_2, and T_3 showed big steady-state error.

As seen in Figs. 8 and 9, when the MSD is located in the first stand, the successive coordination of the roll speed aggravates the performance to the tension control system since the tension transfer was not considered in the control.

(B) With MSD at the last stand: the control objective is to keep $T_3(\infty) = -25$, $T_1(\infty) = T_2(\infty) = 0$.

(1) A speed change only in the V_3 is allowed to achieve the tension control objective without

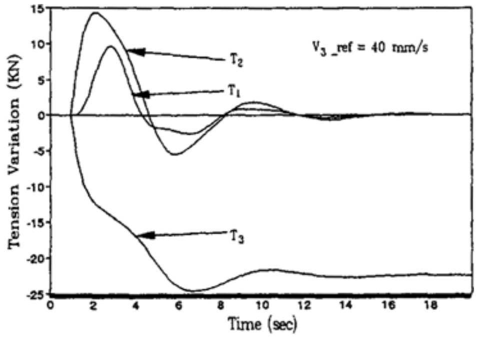

Fig. 10 Tension control without successive control: MSD at last stand.

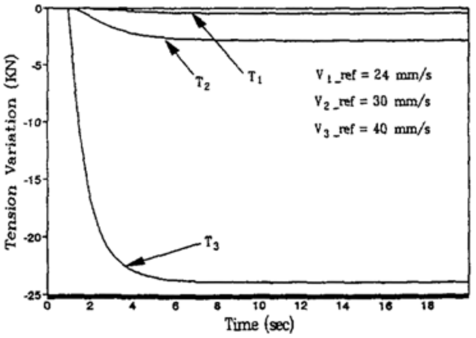

Fig. 11 Tension control with successive control: MSD at last stand.

successive control. The tension variation for given change in speed, V_3, is shown in the Fig. 10. Tension T_1, T_2, T_3 were controlled as desired even though there is small error. The tension variation in the upstream span is transferred to the following spans.

(2) A speed change in the V3 is given to achieve the tension control objective and the speed of the upstream roll is adjusted accordingly to compensate the speed change in the V_3: progressive set-point coordination control. The simulation results are shown in Fig. 11. Tension T_3 was controlled as desired in this case. But, note that the tension in the entrance side of the first stand was assumed constant.

(3) When the entrance tension is not kept constant: $V_1=0$, V_2 and V_3 are changed with step. The simulation results are shown in Fig. 12. The change in tensions T_1, T_2, are bigger than those of Fig. 9 and T_3 are not controlled as desired.

As can be seen from the results, when the successive control method is used with MSD located in the last stand (or downstream stand), the tension in the entrance side of the first stand should be kept constant to properly control the tension in multi-stand rolling systems. Otherwise, the performance of the tension control system is degraded significantly as shown in Fig. 12.

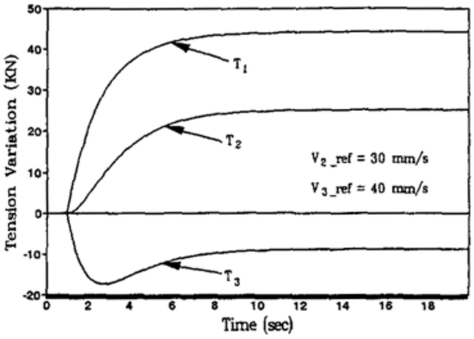

Fig. 12 Tension control with successive control: MSD at last stand, (Entrance tension is not constant).

7. Conclusions

A new mathematical model which describes the relationship among the roll gap, the roll speed, and the strip tension is developed. The tension variation in a metal strip turned out to be very sensitive to the thickness variation as well as to the speed difference at the ends of the metal strip. By using the developed mathematical model, the cancellation mechanism of roll gap control due to the tension interaction could be demonstrated.

A tension control strategy in a multi-stand rolling process is suggested. That is, the MSD should be located in the first stand (or upstream stand) and the tension transfer phenomena is used. The suggested control strategy needs less control efforts and shows better performance than those of the conventional control method in a rolling process.

The developed mathematical model is used to design a controller for the real-time control system. A real-time software for the tension control in a multi-stand rolling system is designed by using the VxWorks real-time scheduler and the Force Target board.

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