ADVANCED TENSION CONTROL BASED ON STATE FEEDBACK FOR REVERSING MILLS

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Abstract: This paper presents a new tension control scheme for reversing mills based on a state feedback approach. The proposed control scheme consists of a feedback of the derivative of the tension to the reel motor torque, which is equivalent to the state feedback of the strip velocity. The state feedback virtually has the effect of enhancing the damping ratio of the tension dynamics and is effective to alleviate its oscillatory nature. With its simple structure, the control scheme has been successfully incorporated into the existing control system of actual reversing mills, increasing the rolling speed and thereby improving the productivity.

Keywords: Automatic process control, Control schemes, Control system analysis, State feedback; Derivative action; Damping ratios; Motor control; Torque control; Industrial control; Steel Industry; Metals.

1. INTRODUCTION

A reversing mill, which contains the rolling stand and tension reels on each side of the stand as its major components, is mainly used for cold rolling of stainless steel and other hard to work material in the steel industry. In reversing mill operations, the strip is passed back and forth between the work rolls of the rolling stand. The strip is reduced in thickness on each pass until the final required thickness is attained. On each pass, the strip is unwound from the entry reel and passed through the roll gap, then rewound onto the delivery reel. The rolling speed is relatively slow at start up. This phase is followed by acceleration to the top speed. Toward the tail end of the strip, a similar process of deceleration is followed.

During the rolling process, tension is applied to the strip on both sides of the rolling stand. The tension is indispensable to make the metal working feasible by alleviating rolling pressure and to assure stable threading of the strip by maintaining a steady mass flow of the strip and thus stable tension control is the key to successful mill operations.

In the reversing mill, tension control is performed by manipulating the torque of the motor for each reel. The tension dynamics, which is represented by the transfer function from the torque to the tension in this case, forms a second-order system. The damping ratio of the second-order system depends strongly on operating conditions. If the damping ratio is small, the dynamics becomes oscillatory and hard to control, which can disturbs smooth start up of each pass and can result in rupturing of the strip. Regarding tension control in reversing mills, some approaches toward multivariable control including thickness (Hoshino, *et al*., 1988; Kondo, *et al*., 1988) have been proposed, but reports on effective methods for controlling the tension itself cannot be found in the literature.

This paper presents a new tension control scheme for reversing mills based on a state feedback approach. The proposed control scheme consists of a feedback of the derivative of the tension to the reel motor torque, which is equivalent to the state feedback of the velocity difference between the outflow of the strip from the stand and the inflow into the reel. The state feedback virtually has the effect of enhancing the damping ratio of the tension dynamics and is effective to alleviate its oscillatory nature and to improve the transient response. With its simple structure, the control scheme has been successfully incorporated into the existing control system of actual reversing mills, increasing the rolling speed and thereby improving the productivity.

2. TENSION CONTROL IN REVERSING MILLS

Fig. 1 shows a schematic diagram of a typical tension control system in revering mills. The back and front tension is controlled by manipulating the entry and delivery reel motor torque, respectively. The torque reference is given basically in a feedforward manner so that the reel rotates synchronizing with the roll. At steady state, the reference coincides with the lord torque, namely the sum of the torque given by the tension and the mechanical loss due to friction. The torque necessary for acceleration and deceleration is added while the rolling speed is changing. The feedforward control is complemented by a feedback controller called ATR (Automatic Tension Regulator), which corrects the torque reference by PI action.

3. MODEL

The tension dynamics between the stand and the delivery reel is considered in this section and later. The tension is governed by the stretch and Young's modulus of the strip. The stretch is given by the time integral of the velocity difference between the outflow of the strip (1) from the stand and the inflow into the reel. Any variables which affect the mass flow balance can be either manipulated variables for tension control or disturbances. Among these variables, the roll velocity and the roll gap are excluded from the tension model and regarded as disturbances for the tension control, because they are not manipulated as a means of tension control. Then the model becomes a simple SISO system with the reel motor torque as the input and the tension as the output.

The reel rotation is governed by the balance between the motor torque q and the load torque q_d by the tension σ. Let the inertia and radius of the reel be denoted J and R, respectively. Let the width and thickness of the strip be denoted W and h, respectively. Since $q_d = WhR\sigma$, the reel velocity v follows the following equation:

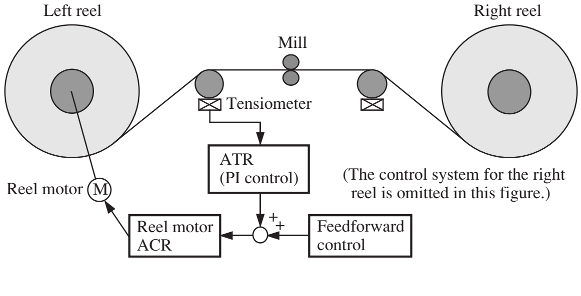

Fig. 1 Schematic diagram of a typical tension control system for reversing mills

$$v = \frac{2\pi R}{J}\int (q - WhR\sigma)\,dt. \tag{1}$$

Let V_R be the roll peripheral velocity, v_S be the strip velocity at the exit of the roll gap, respectively, then the following equation holds:

$$v_S = (1+f)V_R, \tag{2}$$

where f is called forward slip. The forward slip increases in accordance with the tension, which in turn attenuates the change in the tension. Let the effect be linearized around an operating point and denoted $K_{v\sigma}$, namely

$$K_{v\sigma} = v_{S0}\frac{\partial f}{\partial \sigma}, \tag{3}$$

where v_{S0} denotes the strip velocity v_S at the operating point. It should be noted that represents the strength of a natural mechanism which prevents changes in the tension. The tension follows the following equation:

$$\sigma = \int \frac{E}{L}(v - K_{v\sigma}\sigma)\,dt. \tag{4}$$

where E and L denote Young's modulus of the strip and the strip length between the stand and reel, respectively. From Eqs. (1) and (4), the following transfer function representation of the tension model can be obtained:

$$\sigma = \frac{2\pi ER/JL}{s^2 + (EK_{v\sigma}/L)s + (2\pi EWHR^2/JL)}\,q. \tag{5}$$

A block diagram of the model is shown in Fig. 2.

4. CONTROL SCHEME

The natural frequency ω_n and damping ratio ζ of the second-order system (5) are given by the following equations:

$$\omega_n = \sqrt{\frac{2\pi EWH}{JL}}\,R, \tag{6}$$

$$\zeta = \frac{K_{v\sigma}}{2R}\sqrt{\frac{EJ}{2\pi LWH}}, \tag{7}$$

respectively. Eq. (7) shows that the system can be underdamped when $K_{v\sigma}$ is small. The value of $K_{v\sigma}$ depends on operating conditions and becomes small when the thickness or its reduction at the stand is small, or the strip velocity is low. When this is the case, the behavior of the system becomes oscillatory, which can disturb smooth start up of each pass and can result in rupturing of the strip. If the effect of $K_{v\sigma}$ can be enhanced by control, the oscillatory nature of the tension system is alleviated. To this end, a feedback loop of the derivative of the tension to the reel motor torque is

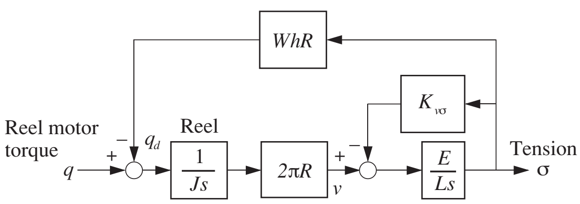

Fig. 2 Block diagram of the tension control system

newly introduced in the proposed control scheme shown in Fig. 3, where the dynamics of ACR (Automatic Current Regulator) is approximated by a first-order lag with the time constant T_C. Since the response of the ACR is much faster than that of the tension system, its dynamics can be ignored when the dynamics of the whole tension control system is considered. Then transfer functions equivalent to the one in Fig. 3 can be obtained as shown in Fig. 4. In either case of (a) and (b), the transfer function is described by the following:

$$\sigma = \frac{2\pi ER/JL}{s^2 + (E(K_{v\sigma}+K/J)/L)s + (2\pi EWHR^2/JL)}\,q. \quad (8)$$

As shown in Fig. 4 (a), this control scheme virtually has the effect of increasing $K_{v\sigma}$ to $K_{v\sigma}+K/J$, and the resulting enhanced damping ratio is the following:

$$\zeta = \frac{K_{v\sigma}+K/J}{2R}\sqrt{\frac{EJ}{2\pi LWH}}. \quad (9)$$

An alternative interpretation for the control scheme is that it is equivalent to the state feedback of the velocity difference between the outflow of the strip from the stand and the inflow into the reel and improves the pole locations for a larger damping ratio.

The Bode plots of the transfer function of the back and front tension are depicted in Figs. 5 and 6, respectively. The value of the damping ratio ζ is 0.12 and 0.21,

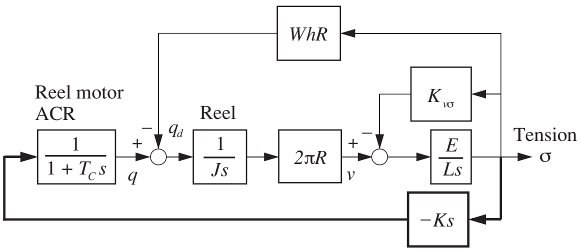

Fig. 3 Block diagram of the tension control sysem with the proposed state feedback

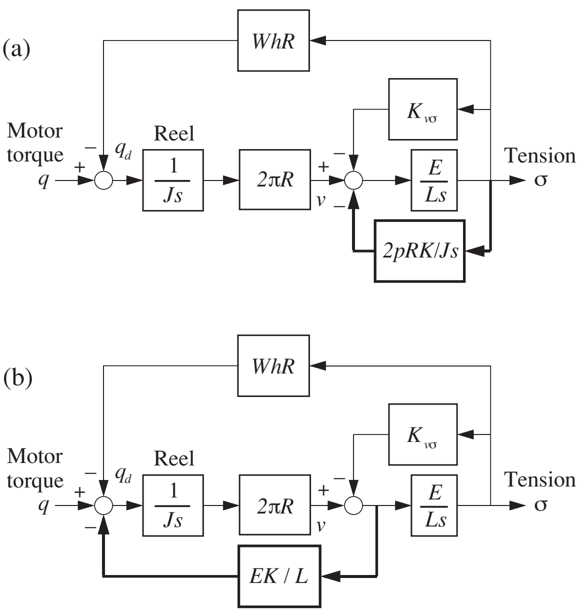

Fig.4 Block diagrams equivalent to Fig.3

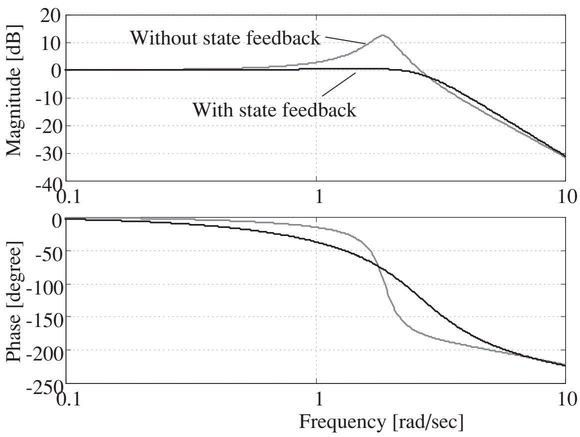

Fig. 5 Frequency response of the back tension dynamics

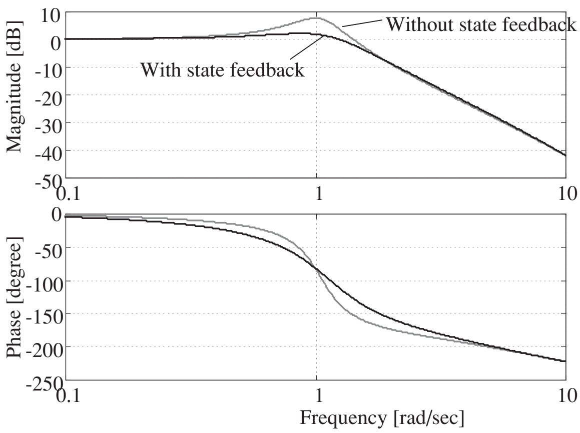

Fig. 6 Frequency response of the front tension dynamics

respectively, and the resulting sharp peak at the natural frequency can be observed in each figure when the state feedback is not applied. The value of the damping ratio ζ is increased to 0.50 and 0.42, respectively, by introducing the state feedback. The peak is lowered indicating that the oscillatory nature of the tension system is alleviated.

5. SIMULATION RESULTS

Performance of the proposed control scheme is demonstrated by simulations. The simulator consists of the dynamics of the reel motor current controller, the tension dynamics, the feedforward compensation of the reel motor torque for the tension reference and the proposed state feedback. A step change in the tension reference is given at $t = 0$. Since the feedback control based on the measured tension (ATR) is not used in this simulation, the torque reference is manipulated only by the feedforward compensation unless the state feedback is applied. The same rolling condition and control parameters as the frequency-domain analysis in Figs. 5 and 6 are assumed.

Responses of the back and front tension at start up are shown in Figs. 7 and 8, respectively. In each figure, the

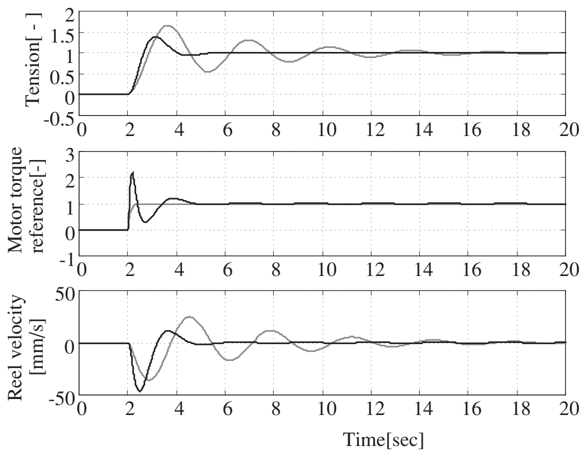

Fig. 7 Simulation results in the case of a step change in the back tension reference

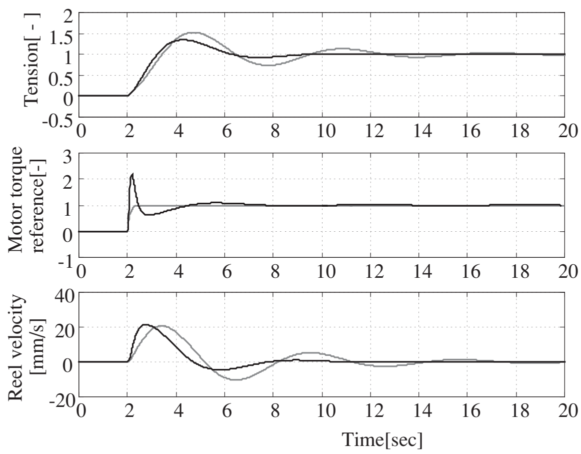

Fig. 8 Simulation results in the case of a step change in the front tension reference

tension and torque is normalized by its reference and its steady state value, respectively. When the state feedback is not applied, the response is rather oscillatory and tension fluctuations are hard to attenuate. In the case of the control system with the state feedback, the damping is enhanced and the overshoot and settling time are significantly improved.

6. EXPERIMENTAL RESULTS

The proposed state feedback has been implemented into the existing control system of a 20-Hi Sendzimir mill and rolling experiments were conducted. The backward difference approximation and a 1st-order low-pass filter are used to implement the feedback of the derivative of tension in the PLC (Programmable Logic Controller). Although the conventional tension controller consists of the feedforward compensation of the reel motor torque in accordance with the tension reference, acceleration, deceleration and the mechanical loss and ATR, only the feedforward control was used and ATR was not applied in the experiments.

Fig. 9 illustrates the velocities of the roll and reel, fluctuations of the back tension and the reel motor torque reference in the case of the existing controller. In the figure, the roll velocity is normalized by its top speed during the experiment and the tension is normalized by its reference. Fig. 10 gives an elongated view of the start-up phase in the same experimental rolling. A rapid increase in the tension is observed when the roll starts rotating. This is caused by the delay of the reel rotation against that of the roll rotation, resulting in a large overshoot and a long settling time. Figs. 11 and 12 shows results when the proposed state feedback is added to the feedforward control. The maximum amplitude of tension fluctuations at the start-up is decreased by a factor of 3 and the settling time is significantly improved. Fig. 12 shows that the state feedback improves the transient response by giving the

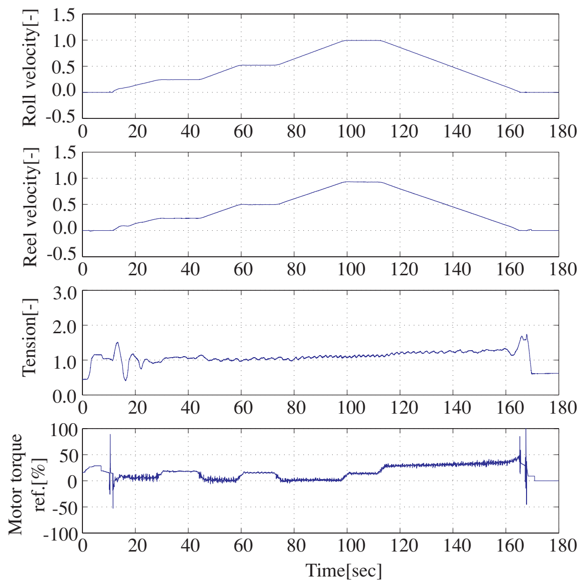

Fig. 9 Performance of the back tension control system without the proposed state feedback

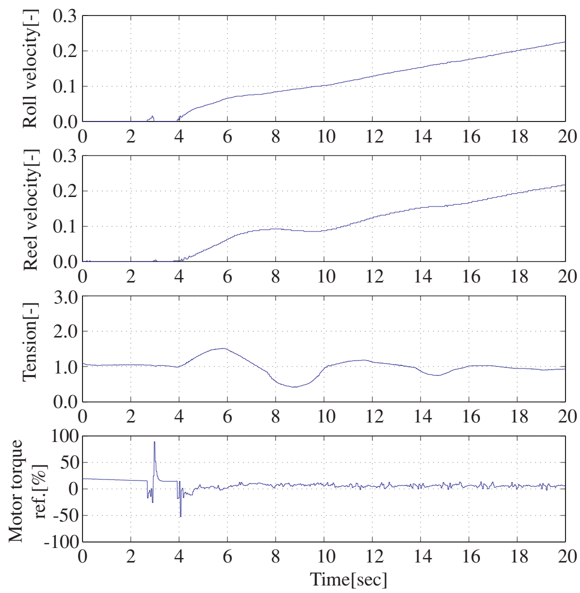

Fig. 10 Performance of the back tension control system without the proposed state feedback (elongated view of the start-up)

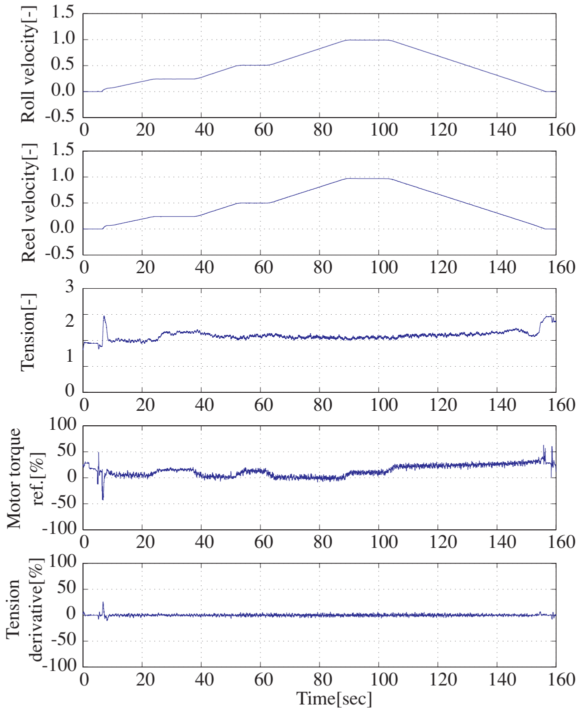

Fig. 11 Performance of the back tension control system with the proposed state feedback

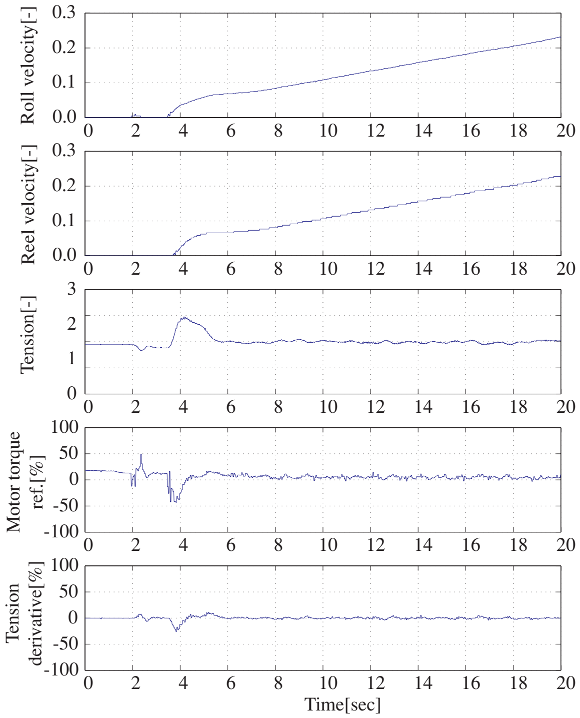

Fig. 12 Performance of the back tension control system with the proposed state feedback (elongated view of the start-up)

motor torque which is necessary for the reel to start rotating harmonizing with the roll. As a result, the reel velocity can follow up the roll velocity after the initial delay, recovering the massflow balance between the roll and reel promptly.

Similar results in the case of the front tension are shown

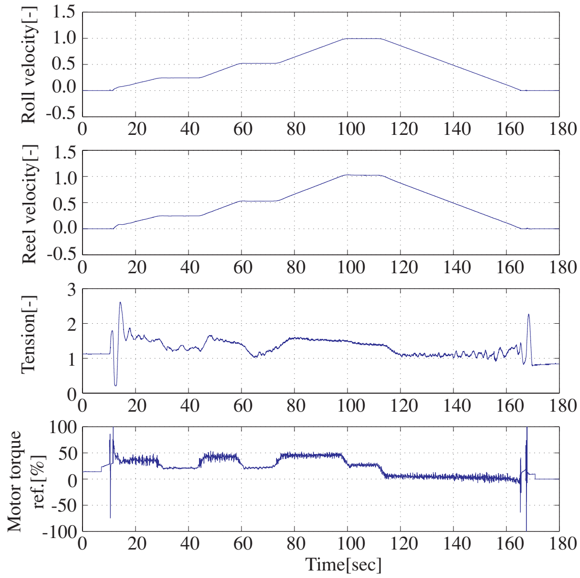

Fig. 13 Performance of the front tension control system without the proposed state feedback

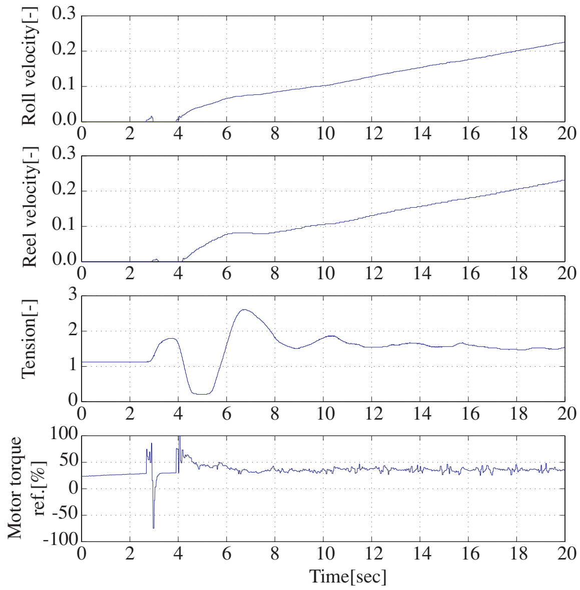

Fig. 14 Performance of the front tension control system without the proposed state feedback (elongated view of the start-up)

in Figs. 13, 14, 15 and 16. The maximum amplitude of the tension fluctuation at the start-up phase is decreased by a factor of 2 as shown in Figs. 14 and 16. In addition, while a fair amount of tension fluctuations caused by acceleration and deceleration can be observed in Fig. 13, they are almost completely suppressed in Fig. 15.

Incorporating the feedback of the derivative of tension into the existing controller can be viewed as introducing D action to the existing PI control, if ATR is used. In these experiments, however, ATR is not used. Therefore, it is more relevant to consider the feedback as a state feedback which improves the tension dynamics. Even if ATR is used together with the state feedback, this interpretation gives a good perspective for parameter

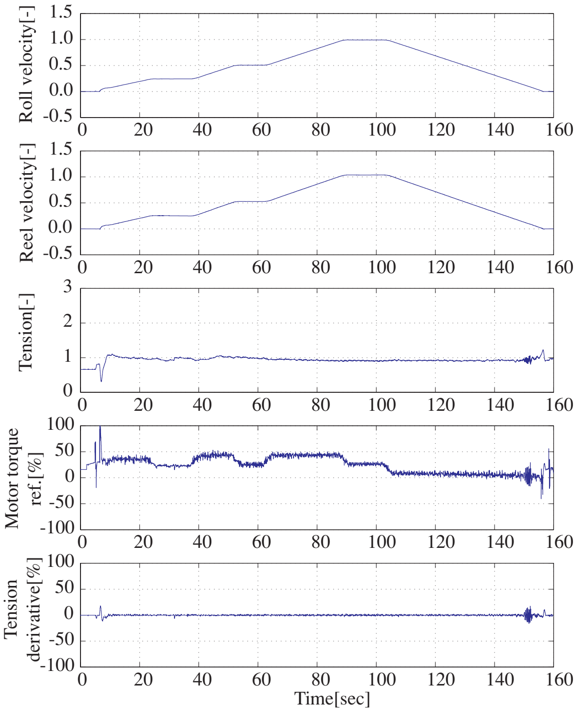

Fig. 15 Performance of the back tension control system with the proposed state feedback

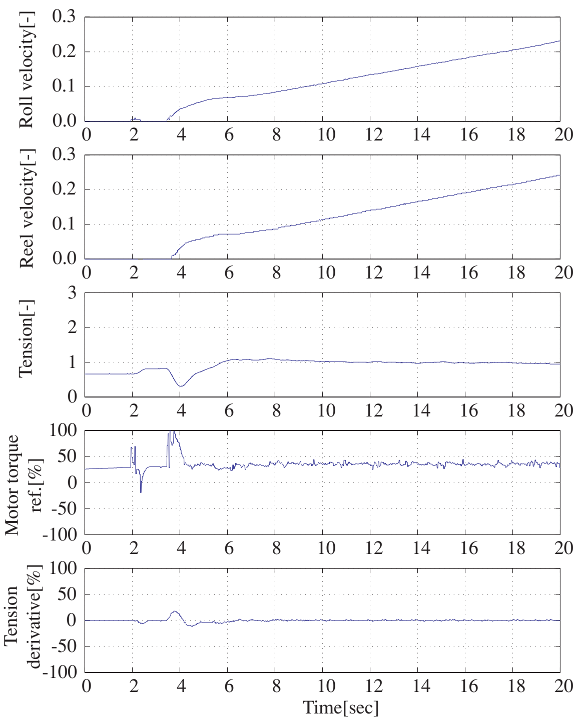

Fig. 16 Performance of the back tension control system with the proposed state feedback (elongated view of the start-up)

tuning.

The stabilized tension control has enabled smooth acceleration and deceleration of the rolling speed on each pass, increasing the maximum rolling speed and thereby improving the productivity.

7. CONCLUSIONS

A new tension control scheme is proposed for reversing mills based on a state feedback approach. The proposed control scheme consists of a feedback of the derivative of the tension to the reel motor torque, which is equivalent to the state feedback of the velocity difference between the outflow of the strip from the stand and the inflow into the reel. The state feedback virtually has the effect of enhancing the damping ratio of the tension dynamics and is effective to improve the transient response by alleviating its oscillatory nature. With its simple structure, the control scheme has been successfully incorporated into the existing control system of actual reversing mills, increasing the rolling speed and improving the productivity.

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