RHC를 기반으로 하는 열간압연 루퍼 제어

RHC based Looper Control for Hot Strip Mill

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Abstract : In this paper, a new looper controller is proposed to minimize the tension variation of a strip in the hot strip finishing mill. The proposed control technology is based on a receding horizon control (RHC) to satisfy the constraints on the control input/state variables. The finite terminal weighting matrix is used instead of the terminal equality constraint. The closed loop stability of the RHC for the looper system is analyzed to guarantee the monotonicity of the optimal cost. Furthermore, the RHC is combined with a 4SID(Subspace-based State Space System Identification) model identifier to improve the robustness for the parameter variation and the disturbance of an actuator. As a result, it is shown through a computer simulation that the proposed control scheme satisfies the given constraints on the control inputs and states: roll speed, looper current, unit tension, and looper angle. The control scheme also diminishes the tension variation for the parameter variation and the disturbance as well.

Keywords : hot strip finishing mill, tension control, looper-tension control, RHC control, 4SID, subspace identification.

I. Introduction

It is well known that the strip quality in the hot strip mill is considerably influenced on a strip tension in the finishing mill [1,2]. The strip tension is mainly caused by the difference of a strip speed which is controlled by a main motor and a looper angle. An unbalanced strip speed often turns to a high(or loose) tension which causes the strip breakage. As a result, it affects the accuracy of product thickness, width, shape, and so on. Thus, this paper studies on a new tension control system for the looper which plays an important role in absorbing the unbalanced strip speed, and keeps the strip tension at its target value [3,4].

In a real plant, most of the looper-tension control systems are a conventional PI control type, which had been applied before a tension meter was invented, so there is no strip tension feedback. Furthermore, there is no compensation of the interaction [5,6] between the looper angle and the tension, and it is very weak to uncertainties. Therefore, the compensation algorithms and gain tables of many controllers are necessary, in particular the gain tables should be continuously tuned to obtain the robust stability and performances.

To improve the defects of the conventional PI control, the MIMO(Multi-Input and Multi-Output) [7,8] control has been studied since 1990s [9,10], of which the remarkable results include an inverse linear quadratic optimal control(ILQ) [11,12], robust H_∞ control [13], model predictive control(MPC) [14], and so on. It is confirmed through the practical application that the above MIMO control systems can effectively consider the interaction between the tension and the looper angle, and considerably improve the control performances. However, they have an unavoidable trade-off between the hardware implementation including sensor/actuator saturation and the robustness for stability and performances. Though the ILQ optimal control has a simple controller structure and its gains can be tuned very easily, it has a weak robustness with respect to the uncertainty of modeling errors and disturbances, and so on. H_∞ control has a good robustness for the uncertainty, but the constraints on the control input/state are not analytically considered. Until now, MPC with terminal equality constraint that all states should go to the origin within a finite horizon was utilized to guarantee the stability for the looper-tension system [14]. However, there is not so much flexibility in choosing the control input to satisfy the terminal equality constraint [15].

In this paper, a new RHC(receding horizon control) scheme combined with a subspace identifier is proposed for the looper-tension system. It satisfies some constraints on control inputs and robustness for parameter variations and disturbances [16]. A looper-tension dynamics is introduced as a state space representation which is obtained from a linear approximation of nonlinear dynamics. On the basis of the obtained state space model, an RHC is developed for the looper-tension system and the finite terminal weighting matrix is used instead of the terminal equality constraint [17]. The RHC controller can handle the constraints on the control input/state and guarantee the stability of the looper-tension system. The parameter variations are caused by a Young's modulus of the strip and the coefficients of the looper load torque. The speed disturbance of the actuator is caused by an operator intervention, a thickness control, and so on. Since the aforementioned RHC has the parameter variation and the disturbance of the actuator, the robustness of the system should be carefully considered. Therefore an adaptive control scheme is constructed to control the tension for the parameter variation, where the looper model is identified by a 4SID(Subspace-based State Space System Identification) algorithm [18-22]. It is shown that the proposed RHC control system has the advantages such as the simpler computation algorithms with the structured LMI(Linear Matrix Inequality), and the robust tracking performance and the robust stability within the limit of constrained control inputs.

The paper is organized as follows: Section 2 gives a brief description of the looper dynamics and its state space representation. In Section 3, the proposed controller including ARHC controller with the finite terminal weighting matrix, the on-line adaptation with the 4SID algorithm is constructed. In Section 4, the simulation results for the parameter variation and

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the constraints are discussed. Conclusions are presented in Section 5.

II. Looper-Tension Dynamics

Fig. 1 shows a looper-tension control system between two stands in the hot strip finishing mill. The looper absorbs the mass-flow unbalance due to the interstand strip speed difference. Model description of this section follows closely that in references [9,11]. By the Newton's second law and Hooke's law, the looper-tension dynamics is described by the following equations:

$$J\ddot{\theta} = -F_1(\theta) - A_s\sigma F_3(\theta) - D\dot{\theta} + T_{lm}, \tag{1}$$

$$\frac{d}{dt}\sigma = \frac{E}{L}\left\{\frac{\partial F_2(\theta)}{\partial \theta}\frac{d\theta}{dt} - (1+f)v_{\mathrm{Re}}\right\}, \tag{2}$$

where the parameters of the looper are represented as

$$\begin{aligned} F_1(\theta) &= T_{lw} + T_{sw} + T_{sb} \\ &= (M_l g)L_g\cos(\theta) \\ &\quad + \left\{\frac{1}{2}(M_s g) + 16Eb\left(\frac{h}{L}\right)^3 H(\theta)\right\}L_l\cos(\theta), \end{aligned} \tag{3}$$

$$\begin{aligned} F_2(\theta) &= L(\theta) - L \\ &= \sqrt{H^2(\theta) + (L_1 + L_l\cos(\theta))^2} \\ &\quad + \sqrt{H^2(\theta) + (L_2 - L_l\cos(\theta))^2} - L, \end{aligned} \tag{4}$$

$$F_3(\theta) = L_l\{\sin(\theta+\beta) - \sin(\theta-\alpha)\}, \tag{5}$$

$$T_{lm} = \phi i_{lm}, \tag{6}$$

where T_{lm} is a looper motor torque, $L(\theta)$ strip length generated by the looper angle, T_{lw} looper weight torque, T_{sw} strip weight torque, T_{sb} strip bending torque, $A_s = bh$, $M_s = \rho A_s(F_2(\theta)+L)$, respectively. Besides, the details of the parameters are referred to the nomenclature.

Note that $F_2(\theta)$, $F_3(\theta)$ in Eqs. (4) and (5) are a geometric strip elongation including the extension due to main roll speed difference and an influence factor relative to the strip tension load, respectively. When the looper angle(θ) increases, $F_2(\theta)$ and $F_3(\theta)$ increase monotonically as shown in Fig. 2. However, $F_3(\theta)$ decreases as $\theta>50$[*degree*]. Nonlinear dynamics given as in Eqs. (1) and (2) is linearized by the approximation technique using Taylor's series expansion. As a result, the state space representation of a linearized model is given as follows:

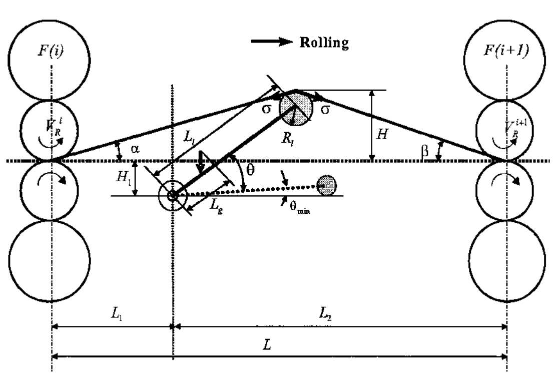

그림 1. 루퍼 시스템의 개략도.

Fig. 1. Configuration of looper system.

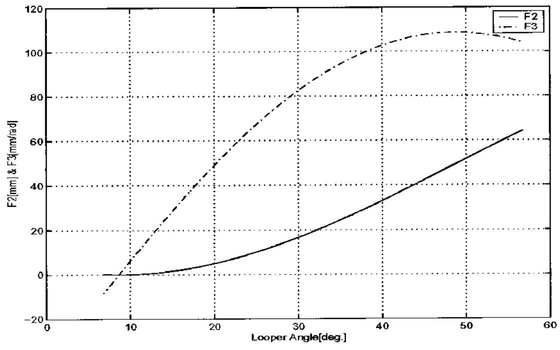

그림 2. 루퍼 각도와 $F_2(\theta), F_3(\theta)$와의 관계도.

Fig. 2. Relation between looper angle and $F_2(\theta), F_3(\theta)$.

$$\begin{aligned} \dot{x}(t) &= A_c x(t) + B_c u(t), \\ y(t) &= C_c x(t) + D_c u(t), \end{aligned} \tag{7}$$

where $x\in\Re^n$ is a state and $u\in\Re^m$, $y\in\Re^m$ are a control input and a measured output(n=5, m=2), respectively. They are defined as $x = [\delta\sigma\ \delta\theta\ \delta\dot{\theta}\ \ \delta v_{Re}\ \delta i_{lm}]^T$, $u = [\delta v_{Re}^{ref}\ \delta i_{lm}^{ref}]^T$, $y = [\delta\sigma\ \delta\theta]^T$. In Eq. (7), we proposed the $5th$ order matrices of the looper system as follows, respectively. The effectiveness of the $5th$ order looper system is verified in [11,13].

$$A_c = \begin{bmatrix} -3.002 & 0 & 880.3 & 0 & -22.8 \\ 0 & 0 & 1 & 0 & 0 \\ -2.9 & -119.1 & -36.5 & 0.17 & 0 \\ 0 & 0 & 0 & -13.3 & 0 \\ 0 & 0 & 0 & 0 & -3.12 \end{bmatrix},$$
$$B_c = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 6.7 \\ 3.1 & 0 \end{bmatrix},\ C_c = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix},\ D_c = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}. \tag{8}$$

III. ARHC based Tension Control System

The control system proposed in this paper has a structure of an adaptive RHC(ARHC) system based on an on-line subspace identifier to enhance the robustness with respect to parameter variations. To design the RHC controller which satisfies some constraints subject to control input/state variables, the continuous-time model in Eq. (7) is represented as the following time-invariant discrete system with input and state constraints:

$$x_{k+1} = A_k x_k + B_k u_k, \tag{9}$$

subject to

$$\begin{cases} -u_{\lim} \le u_k \le u_{\lim}, & k = 0, 1, \cdots, N-1 \\ -g_{\lim} \le Gx_k \le g_{\lim}, & k = 0, 1, \cdots, N \end{cases} \tag{10}$$

where $u_{lim}\in\Re^m$, $G\in\Re^{n_g\times n}$ and $g\in\Re^{n_g}$. It is assumed that $u_k = 0$ and $Gx_k = 0$ satisfy the constraint (10).

The performance criterion can be written as follows:

$$J(x_k, k) = \sum_{i=0}^{N-1}(x_{k+i|k}^T Q x_{k+i|k} + u_{k+i|k}^T R u_{k+i|k}) \tag{11}$$

$$+ x_{k+N|k}^T \Psi x_{k+N|k},$$

where N is a horizon size, $Q \geq 0$, $R > 0$ and $\Psi > 0$ are the state weighting matrix, the input weighting matrix and the terminal weighting matrix, respectively, and set to $Q = \Psi = I^{n \times n}$, $R = I^{m \times m}$(I:identity matrix).

We introduce so-called *invariant ellipsoid* property which can be interpreted in terms of quadratic stability. Let us suppose that there exists a $K \in \Re^{m \times n}$ and a positive definite matrix $P \in \Re^{n \times n}$ such that

$$(A+BK)^T P(A+BK) - P \leq 0. \tag{12}$$

Then the optimization problem minimizing $J(x_k, k)$ subject to the constraint (10) is always feasible for all $k \geq 0$ and for all initial states $x_0 \in \varepsilon_\Psi$ where

$$\varepsilon_\Psi = \{\xi \in \Re^n \mid \xi^T \Psi \xi \leq 1\}. \tag{13}$$

Also, $x_k = 0$ is the exponential stable equilibrium of the closed loop system with the receding horizon controller stemming from this optimization problem, for all initial states $x_0 \in \varepsilon_\Psi$.

In order to utilize the RHC, the state and input of the system equation (9) need to be augmented. First, we define the augmented variables X_k, U_k and X_{k0} as

$$X_k = \begin{bmatrix} x_{k|k} \\ x_{k+1|k} \\ \vdots \\ x_{k+N|k} \end{bmatrix}, \; U_k = \begin{bmatrix} u_{k|k} \\ \vdots \\ u_{k+N-1|k} \end{bmatrix}, \; X_{k0} = \begin{bmatrix} x_k \\ 0 \\ \vdots \\ 0 \end{bmatrix}. \tag{14}$$

Then the following equation holds and the performance index (11) is written by as follows:

$$X_k = \hat{A} X_k + \hat{B} U_k + X_{k0}, \tag{15}$$

$$J(x_k, k) = X_k^T \hat{Q} X_k + U_k^T \hat{R} U_k, \tag{16}$$

where $\hat{Q}$ and $\hat{R}$ are the augmented weighting matrix, $\hat{A}$ and $\hat{B}$ are the augmented matrix of the A, B and $\hat{Q}$ includes Ψ in the last diagonal component.

The optimization problem (16) can be expressed as the following *quadratic constrained quadratic program(QCQP)*:

$$\min_{U_k} J(x_k, k), \tag{17}$$

subject to

$$\begin{cases} -\hat{u}_{\lim} \leq U_k \leq \hat{u}_{\lim} \\ -\hat{g}_{\lim} \leq \hat{G} U_k + \hat{g}_0 \leq \hat{g}_{\lim} \\ (A^N x_k + \bar{B} U_k)^T \Psi (A^N x_k + \bar{B} U_k) \leq 1 \end{cases} \tag{18}$$

where

$$\hat{u}_{\lim} = \begin{bmatrix} u_{\lim} \\ \vdots \\ u_{\lim} \end{bmatrix}, \; \hat{g}_{\lim} = \begin{bmatrix} g_{\lim} \\ \vdots \\ g_{\lim} \end{bmatrix}, \; \bar{G} = \begin{bmatrix} G & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & G \end{bmatrix},$$

$$\hat{G} = \bar{G} \hat{W}, \; \hat{g}_0 = \bar{G} \hat{w}_0$$

and

$$\bar{B} = [A^{N-1} B \;\; A^{N-2} B \; \cdots \; B].$$

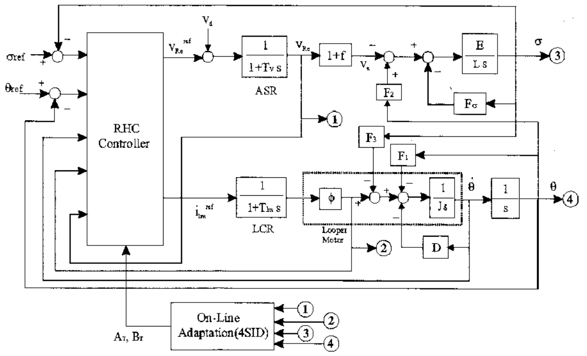

그림 3. ARHC의 제어기 구조.

Fig. 3. Controller structure of ARHC.

Finally the control input(u_k) is represented as follows:

$$\begin{cases} u_k = [1, 0, \cdots, 0] U_k^*, & k = 0, 1, \cdots, N-1 \\ u_k = H x_k, & k = N, N+1, \cdots \end{cases} \tag{19}$$

where H is a feedback control gain. Note that RHC scheme, namely, finite receding horizon optimal control with a finite terminal weighting matrix, guarantees the stability of the closed loop control system, and the cost horizon size can be selected more freely than that of the infinity horizon.

Now, we identify system matrices(A_k, B_k) in Eq. (9) using an on-line subspace identification algorithm, so called 4SID (Subspace-based State Space System Identification), in order to enhance the robustness of the RHC. The 4SID is effective in identifying a discrete-time state space model of MIMO systems. The details of the algorithm can be found in [18-22].

Fig. 3 shows the structure of ARHC. The input, output variables of the system are selected from the dynamics analysis. The input variables of the block '*RHC controller*' are six including the 5 states($x_k = [\delta\sigma \; \delta\theta \; \delta\dot{\theta} \;\; \delta v_{Re} \; \delta i_{lm}]^T$) and the system matrices(A_T, B_T) calculated by the 4SID. The output variables are two control inputs($u_k = [\delta v_{Re}^{ref} \; \delta i_{lm}^{ref}]^T$). The inputs of the block '*on-line adaptation*' are two control inputs and two outputs($[\delta v_{Re}^{ref} \; \delta i_{lm}^{ref} \; \delta\sigma \; \delta\theta]^T$) and the output is the system matrices.

IV. Simulation Results and Discussions

The system parameters of Pohang no.2 hot strip mill in POSCO were used for the simulation. The simulation results show the variation of the strip tension, the looper angle and the control inputs, where the references of the unit tension and the looper angle are 8.6[N/mm^2], 20[*degree*], respectively.

In Eqs. (1) and (2), the critical system parameters are considered as Young's modulus E, of which nominal value is set to E=117,600 [N/mm^2], and the parameters $F_2(\theta)$, $F_3(\theta)$. The RHC controller is only adopted until 4[*sec*](200 samples) to gather the data, and the results between RHC and ARHC are compared during 4~10[*sec*]. The sampling time of the simulation is 20[*msec*]. The on-line model is updated every 20 samples(0.4[*sec*]) after 4[*sec*]. The constraints of the input and state for the RHC are expressed as follows:

$$\begin{cases} -1 \leq u_{1,k+i|k} \leq 1, -0.3 \leq u_{2,k+i|k} \leq 0.3, \; i = 0, 1, \cdots, N-1 \\ -6 \leq Gx_{1,k+i|k} \leq 6, -0.14 \leq Gx_{2,k+i|k} \leq 0.14, \; i = 0, 1, \cdots, N \end{cases} \tag{20}$$

where N is set to 5. The coefficient matrices (A_k, B_k, C_k, D_k) are adaptively updated from the on-line identification.

1. Control input and disturbance attenuation

In ARHC scheme, it is one of the most important features that the control input satisfying some constraints subject to input and state variables is obtained. Under the existence of a speed disturbance, Fig. 4 represents the control inputs in case of RHCC(Receding Horizon Control with Constraints) and RHCU(Receding Horizon Control for Unconstrained systems). From the figure, it is shown that RHCC satisfies the constraints given in Eq. (20), namely upper and lower-limits of v_{Re} are $\pm 1[mm/sec]$. It is shown in Figs. 5 and 6 that the tension variation and the control input(v_{Re}) of ARHC are decreased by 74[%], 82[%], respectively, rather than that of the conventional PI in case of the speed disturbance. It is also known that the proposed ARHC scheme is very effective in controlling the strip tension in the hot strip mill process.

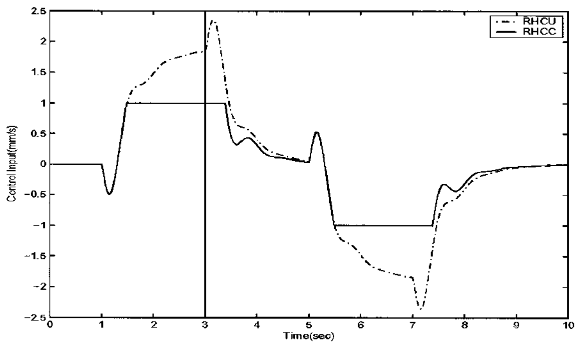

그림 4. ARHC의 제어입력(v_{Re}).

Fig. 4. Control input(v_{Re}) of ARHC.

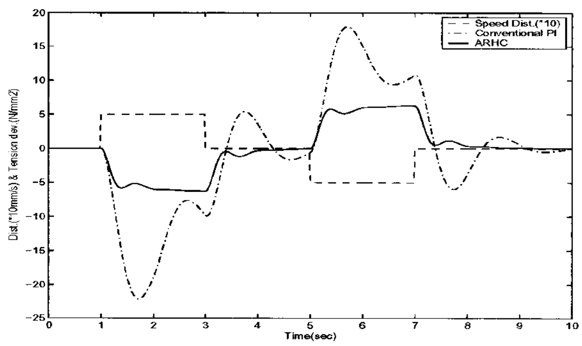

그림 5. 속도 외란에 대한 PI와 ARHC의 장력 변동.

Fig. 5. Strip tension of conventional PI and ARHC for speed disturbance.

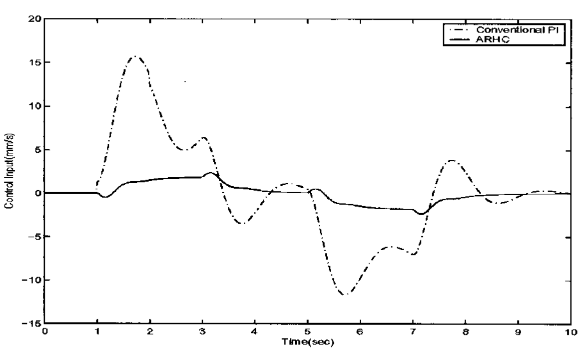

그림 6. PI와 ARHC에 대한 제어입력(v_{Re}).

Fig. 6. Control input(v_{Re}) of conventional PI and ARHC.

2. Robustness for parameter variation

The proposed ARHC control system takes an adaptive control system combined with an on-line subspace model identifier, which aims to enhance the robustness for the variation of the system parameters. In this paper, we consider the effect of the parameters such as E, $F_2(\theta)$, $F_3(\theta)$ in looper-tension dynamics as shown in Eqs. (1) and (2).

Even though Young's modulus E is a function of strip temperature, carbon and time, it is assumed that E is a constant in the real plant. Therefore, it is necessary to analyze the robustness for the variation of E. Fig. 7 shows the tension variation, in case that E varies as pulse type within the limit of ±20[%] during

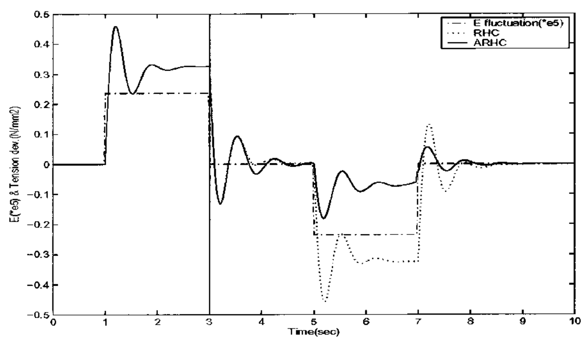

그림 7. E 변동에 대한 압연 판의 장력.

Fig. 7. Strip tension for E variation.

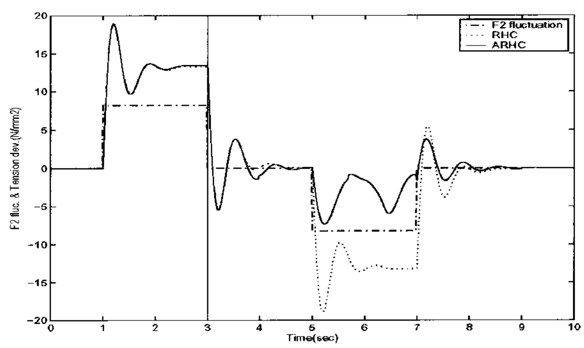

그림 8. F_2 변동에 대한 압연 판의 장력.

Fig. 8. Tension for F_2 variation.

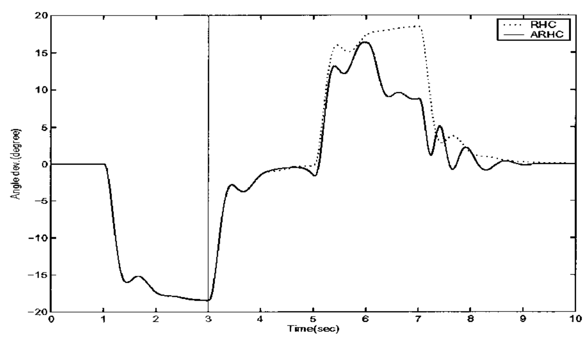

그림 9. F_2 변동에 대한 루퍼 각도.

Fig. 9. Looper angle for F_2 variation.

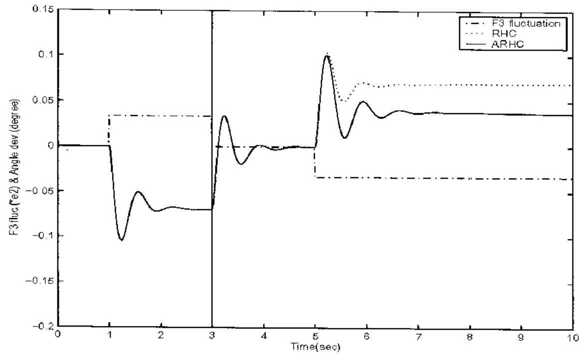

그림 10. F_3 변동에 대한 루퍼 각도.

Fig. 10. Looper angle for F_3 variation.

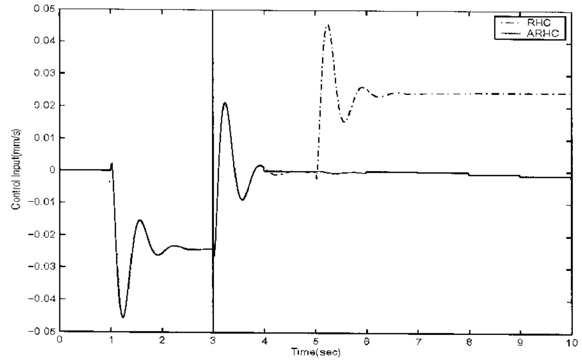

그림 11. F_3 변동에 대한 제어입력(v_{Re}).

Fig. 11. Control input(v_{Re}) for F_3 variation.

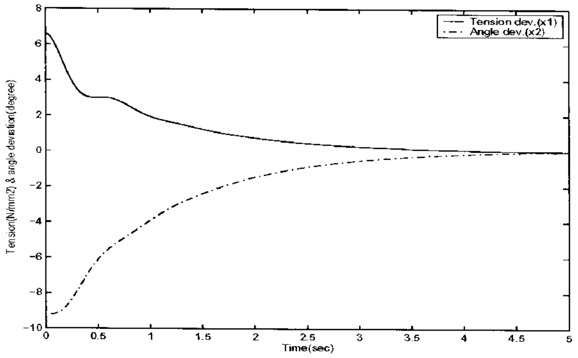

그림 12. 상태변수($\delta\sigma$, $\delta\theta$)의 시간에 따른 변화.

Fig. 12. Trajectory of two states($\delta\sigma$, $\delta\theta$).

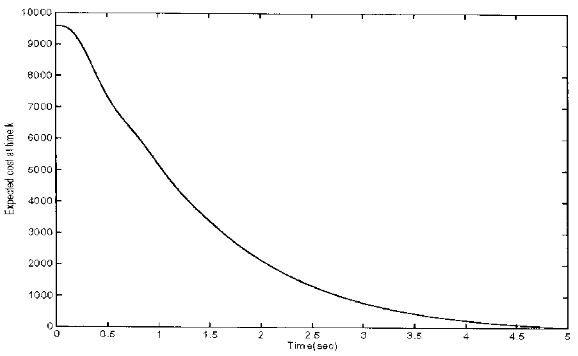

그림 13. 시간 k에서 예상되는 성능지수.

Fig. 13. Expected cost at time k.

1~3[*sec*], 5~7[*sec*]. It is known from Fig. 7 that the tension variation of ARHC decreased by 50[%] rather than that of RHC during 5~7[*sec*]. The tension variation of ARHC after 7[*sec*] can be reduced by updating the model with the small sample size for the adaptation.

F_2 is varied by the length of the strip by the looper angle(θ) and it generates the tension variation. Figs. 8 and 9 show the variation of the tension and the looper angle, respectively. Since F_2 is the effective coefficient representing the variation of the tension as a result of the angle, the ±20[%] variation for F_2 brings about large tension variation. Normally it is not easy to eliminate the variation of F_2 because it causes by the mass-flow unbalance between two stands. However the proposed ARHC can minimize the variation of F_2 through the on-line model adaptation. From Fig. 8, the tension variation of the ARHC decreased by 50[%] rather than that of RHC.

F_3 variation generates the variation of the tension torque and it is the one of the causes of the mass-flow unbalance. F_3 is the parameter to represent the angle variation as previously stated. Figs. 10 and 11 show the variation of the looper angle and the control input(v_{Re}), respectively. The looper angle for the F_3 variation is less fluctuating than that of F_2. The control input of the ARHC is also smaller than that of RHC as shown in Fig. 11.

3. Stability analysis

The closed-loop stability of the RHC is analyzed for time-invariant systems which guarantee the monotonicity of the optimal cost. It is shown through the simulation that zero states and the cost monotonicity at time k are satisfied. Fig. 12 shows the trajectory of two states($\delta\sigma$, $\delta\theta$). The over-tension and under-angle deviations are released by increasing the main motor speed and the looper current, respectively. Fig. 13 shows the expected cost at time k. Since the looper-tension system satisfies the cost monotonicity, the asymptotical stability is guaranteed by the reference [17].

V. Conclusions

This paper proposed a new tension control scheme for the looper in the hot strip finishing mill. The proposed control scheme is designed on the basis of a receding horizon control(RHC) combined with an on-line subspace identifier(4SID). The simulation results are summarized as follows: The RHC algorithm was very useful in designing a controller which simultaneously satisfied the constraints subject to control input as well as the tracking performance of interstand strip tension. The tension variation of the proposed ARHC with constraints was decreased by 74[%] compared with the conventional PI for the speed disturbance. As a consequence, it is shown that the proposed ARHC scheme is very effective in controlling the strip tension by the looper.

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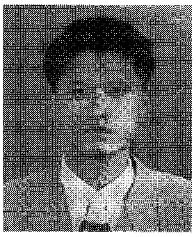
Appendix A. Nomenclature

b	strip width [mm]	D	damping factor [$N\,sec/mm$]
E	Young's Modulus [N/mm^2]	f	forward slip ratio
g	acceleration of gravity [mm/s^2]	h	thickness at delivery of finishing mill [mm]
i_{lm}	looper motor current [A]	J	looper inertia [Nmm^2]
M_l	total mass of the looper arm and looper roll [Kg]	M_s	strip mass [Kg]
T_{ob}	time constant of observer [sec]	T_v	time constant of LCR [sec]
v_d	speed disturbance [mm/s]	v_e	speed difference of strip for inter-stand [mm/s]
v_{Re}	speed difference of roll for inter-stand [mm/s]		

Greek Letters

ϕ	torque constant [Nmm/A]	ρ	density of the strip [Kg/mm^3]
σ	inter-stand tension[N/mm^2]	θ	looper angle[$degree$]



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