H^∞ Speed Control for Hot Rolling Mill Drives using Mixed Sensitivity Minimization

혼합감도최소화를 이용한 열간압연 구동기에 대한 H^∞ 속도제어

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요 약 : 포항제철 2열연공장의 사상압연기에 사용되고 있는 DC 모터를 가지는 열간압연 구동기에 대한 견실 H^∞ 속도제어기 설계방법을 제안한다. 기존에는 PI 제어기법을 이용하여 속도를 제어하고 있으므로 불확실성과 외란 등이 존재할 경우 양호한 제어 성능을 얻기 힘들다. 이를 해결하기 위해 주파수 하중함수를 가지는 혼합감도최소화 문제를 설정하여 견실성을 보장하는 H^∞ 속도제어기를 설계한다. 이때 주파수 하중함수는 루프쉐이핑기법을 이용하여 주어진 구동기 플랜트에 적합하도록 선택한다. H^∞ 속도제어기 설계는 Pasek이 제시한 DC 모터의 모델링 방법에 의해 얻어진 모델을 포함하는 구동기 모델에서 속도제어기 부분을 제외한 모델을 대상으로 한다. 제안한 견실 속도제어기 설계방법은 파라미터 변화나 부하토크 변동 등의 외란에 대하여 폐루프 시스템의 견실안정성과 원하는 속도에 대해 좋은 추적 성능을 보인다. 제어 대상인 포항제철 2열연공장의 열간압연 구동기에 대한 시뮬레이션을 통해 기준속도 추적성, 응답속도, 불확실성과 외란에 대한 견실성 등의 성능이 기존의 PI 속도제어기보다 양호함을 확인하므로써 제안한 견실 H^∞ 속도제어기 설계방법의 타당성을 보인다.

Keywords: robust H^∞ control, speed control, hot rolling mill drive, loop shaping, mixed sensitivity minimization

I. Introduction

The increasing demands for higher quality steel strips and higher strip thickness precision in the steel industry have led to better performance requirements. To meet these requirements, many factors such as speed, shape, thickness, and cooling must be controlled accurately in the hot rolling process. The hot rolling process of #2 hot rolling mill of POSCO(Pohang Iron & Steel Co.) has a roughing mill and a finishing mill. The finishing mill has 7 stands with drive system. In here, the drive system of the finishing mill is treated. The hot rolling mill drive system includes 2 DC motors, a thyristor converter, a rolling mill mechanical system, and a drive system controller. The mechanical power is transferred from drive system to work rolls and backup rolls. The work rolls are used directly for hot rolling. The thyristor converter is applied for power supply and power control to DC motor used as the actuator of drive system. To control the speed, the drive system controller is composed of a PI speed controller, a current controller, and a voltage controller. And speed PLC(programmable logic controller) gives reference speed signal to drive system. In practical application, the hot rolling mill drive system operates under wide range of load torque changes and system parameter variations. PI speed controller, however, cannot supply good robust performance under these situations. Thus a robust H^∞ control scheme is frequently used to ensure a specified dynamic response under above conditions. For robust controller design, Kimura[1] derived J-lossless coprime factorization, Glover and Doyle[2] proposed H^∞ controller design method in state space, and Doyle *et al.*[3] derived general H^∞ solution. Many researchers have tried to apply robust control theory to steel processes. To control the speed of drive system, Dhaouadi *et al.*[4] designed two-degree-of-freedom robust speed controller for rolling mill drives, Iwasaki *et al.*[5] derived the robust speed control method using torque feedforward control for induction motor drives. However, the first method needs not only the values of motor torque and motor speed but also an unknown load torque disturbance and internal states such as the shaft torque and the load speed. Unfortunately, some of these values cannot be measured accurately. Also, not the parameter uncertainties and disturbances of drive system but the effects of mechanical resonance are mainly treated in [4]. The second one using load torque observer and torque feedforward control method is inaccurate in transient state. So, the error of load torque observer has a bad effect on speed control. As another application, Asano *et al.*[6] presented robust molten steel level controller for continuous casting.

In this paper, an H^∞ speed controller design method for hot rolling mill drives of POSCO is proposed and the model of DC motor is presented through Pasek's method. For designing a speed controller, mixed sensitivity minimization method[7] and loop shaping technique[8] are used. For the drive system model, weighted mixed sensitivity minimization method with sensitivity minimization and complementary sensitivity minimization is used for guaranteeing the robust stability of closed loop system with parameter variations and load torque disturbances. And loop shaping technique is used for improving speed tracking performance. The principal idea of loop shaping is that the maximum singular values of

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closed loop transfer functions can be directly determined over appropriate frequency ranges by the singular values of the corresponding open loop transfer functions.

The speed control performance from the proposed controller is compared with that from the existing PI controller through the computer simulation. As simulation conditions, reference speed signals and load torque disturbances are selected as step signals and pulse signals. And parameter variations of current sensor gain are also treated. Then the characteristics of overshoot, steady state error, robustness, and tracking ability are investigated. Some of simulation results will be presented in section IV.

For quality improvement of hot strips using the proposed H^{∞} speed control method in field application, the speed signals of hot rolling mill drives must be linked and regulated properly.

II. Hot rolling mill drive system

The hot rolling mill drive system is shown in Fig. 1. It is composed of 2 DC motors driven by the thyristor converter, drive system controller and rolling mill mechanical system such as coupling, gear drive, and spindle. The drive force of DC motor is transferred sequentially to coupling, gear drive, spindle, and work rolls and backup rolls. The work rolls are used for rolling hot strips and the backup rolls with no drive force and high mass support work rolls. The mechanical characteristics such as motor and roll inertia, spindle stiffness, and gear backlash, are assumed to be treated as uncertainties in drive system.

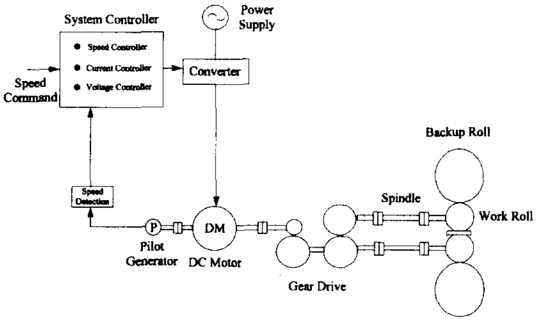


Fig. 1. The hot rolling mill drive system.

Main AC power is transformed to DC power through transformer with 12-pulse PCR(phase controlled rectifier) and DC motor is drived by the converted DC power. DC power generated by the 12-pulse PCR has small ripple. By controlling firing angle of the thyristor converter, DC power can be varied up to 1200V. In break mode, DC motor is drived by reverse current and 6-pulse PCR structure.

The drive system controller is composed of speed controller, current controller, and voltage controller, sequentially. Each controller uses PID control scheme. Speed signal of speed controller is made from the difference of reference speed signals from speed PLC and speed feedback signal of PG(pilot generator) installed to motor shaft. Current and voltage signals of current and voltage controller are also compensated by those from current and voltage sensors of DC motor, respectively. Voltage signal drives DC motor via the thyristor converter. Because current change of current controller is more fast than speed change of DC motor, current controller can guarantee fast response in drive system. At the same time, current controller limits over-current in the system controller and reduces the effect of external disturbances. And voltage and current sensors protect drive system from abnormal operation. The existing PI speed controller cannot supply good robust performance in speed control under drive system parameter uncertainties and disturbances. Therefore the robust H^{∞} control scheme is required to ensure good speed control under these conditions.

III. Drive system model and control system formulation

The accurate drive system model is required to obtain good speed control performance. POSCO has the drive system model except DC motor model. Although the DC motor model is very important to design speed controller, it is very difficult to get the motor model under on-line condition. The linear model of DC motor is given as

$$\begin{aligned} V &= K_e\omega + R_a i + L_a\frac{di}{dt} \\ T &= J\frac{d\omega}{dt} + B\omega + T_f \end{aligned} \tag{1}$$

where V is magnitude of the applied armature step voltage, K_e is voltage constant of the DC motor, ω is angular velocity of the motor shaft, R_a is armature resistance effect, i is motor armature current, L_a is armature inductance effect, T is developed torque, J is inertial effect, B is viscous damping effect and T_f is friction effect, respectively. Here, the motor model is obtained using Pasek's method[9], which is a measurement technique that all the parameters of the linear model of DC motor can be determined by observing a single current response of the motor to a step input of armature voltage. Fig. 2 shows a typical test circuit for Pasek's method which is tested under zero load condition. The whole basis for the parameter determination technique described in [9] is that the current response for each model is unique, and contains all the information needed to quantify the parameters.

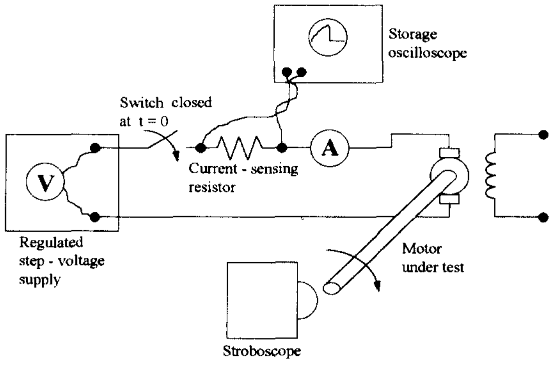


Fig. 2. The test circuit for Pasek's method.

The parameters of DC motor are determined from the experimental equation proposed by Pasek. From the obtained current response, the method is based on

$$\frac{i(2t_1)}{i(t_1)} = \frac{i(t_1)}{I_{sc}}, \tag{2}$$

where $i(t_1)$ is peak current at time t_1 for all second order models, $i(2t_1)$ is armature current at time $2t_1$ for all second order model, and $I_{sc}(=V/R_a)$ is short circuit armature current. After finding a ratio $i(2t_1)/i(t_1)$, electrical time constant and mechanical time constant can be obtained through the test circuit in Fig. 2. From the obtained time constants, the transfer function of DC motor model from V to w is constructed as follows:

$$\frac{\omega(s)}{V(s)} = \frac{6.74}{s^2+53s+601.4}. \tag{3}$$

The obtained DC motor has no overshoot and characteristic roots in the left half plane. When the step input is applied to the hot rolling mill drive system, the responses of the modeled drive system with the modeled DC motor and the practical drive system are much the same.

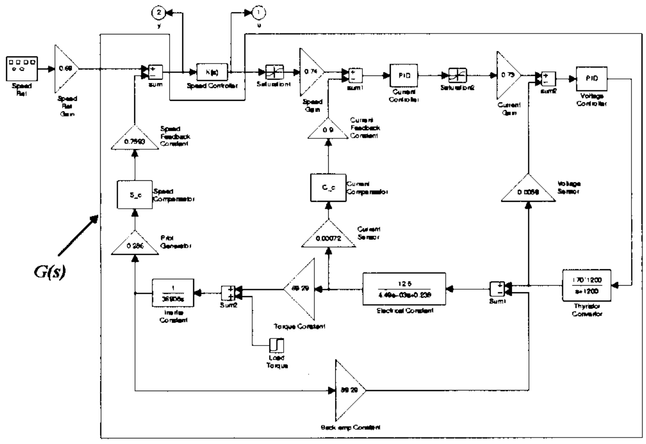


Fig. 3. The hot rolling mill drive system model.

The modeled hot rolling mill drive system with DC motor as the actuator is shown in Fig. 3. The nominal plant $G(s)$ for speed control is constructed from the full model of drive system except speed controller part as follows:

$$G(s) = \frac{(1.996\,\mathrm{E9})s^2 + (2.007\,\mathrm{E12})s + (1.178\,\mathrm{E13})}{\begin{array}{c}s^7 + 2273s^6 + (1.822\,\mathrm{E6})s^5 + (5.806\,\mathrm{E8})s^4 \\ + (1.114\,\mathrm{E11})s^3 + (3.305\,\mathrm{E12})s^2 + (2.247\,\mathrm{E13})s\end{array}}. \tag{4}$$

Thus the drive system can be simplified to the system configuration of Fig. 4 in which the H^{∞} speed controller will be designed.

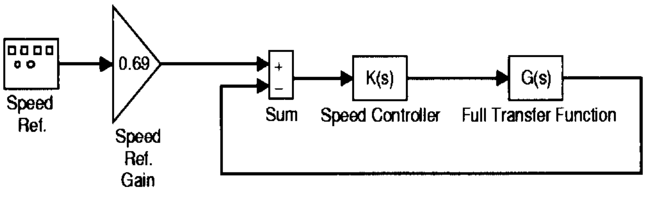


Fig. 4. Simplified drive system for speed controller design.

Ⅳ. H^{∞} speed controller design and computer simulation

In this section, an H^{∞} speed controller design method using Glover and Doyle's H^{∞} controller design algorithm and loop shaping technique, is presented. And H^{∞} speed controller to the drive system in #2 hot rolling mill of POSCO will be designed. The basic objective in controller design is to guarantee robust stability and good performance. Loop shaping is used for tradeoff between performance and robustness with the guaranteed stability properties of H^{∞} design method. Generally, it is reasonable to treat performance problem in low frequency range and to consider robustness in high frequency range[10]. The sensitivity minimization is focused on disturbance rejection, but the speed controller should satisfy the sensitivity minimization and robust stability simultaneously. Therefore, it is necessary to formulate mixed sensitivity H^{∞} control problem. The closed loop system for mixed sensitivity minimization problem in hot rolling mill drive system is depicted in Fig. 5, where $G(s)$ is nominal plant, $K(s)$ is the speed controller, $\alpha(s)$ is frequency weighting function for loop shaping, $W_s(s)$ is weighting function for sensitivity minimization, $W_t(s)$ is weighting function for complementary sensitivity minimization, w is exogenous input, y is measured output, and r is reference speed input, respectively. The complementary sensitivity function from w to z_1 is represented by

$$\begin{aligned}\frac{z_1}{w} &= W_t G_s K_a (I+G_s K_a)^{-1} \\ &= W_t GK(I+GK)^{-1}\end{aligned} \tag{5}$$

and the sensitivity function from w to z_2 is described as

$$\frac{z_2}{w} = W_s(I+G_sK_a)^{-1} = W_s(I+GK)^{-1} \tag{6}$$

where $K(s)=\alpha(s)K_a(s)$ and the shaped plant $G_s(s)=\alpha(s)G(s)$.

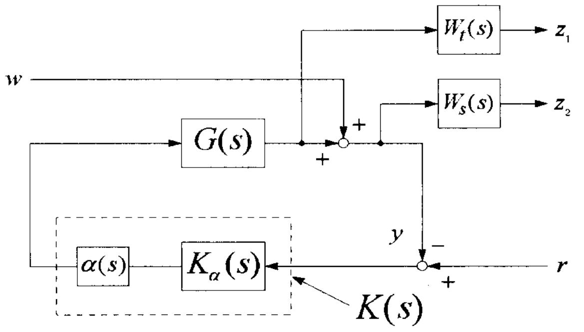


Fig. 5. The closed loop system for mixed sensitivity minimization problem.

Mixed sensitivity minimization problem for H^{∞} speed controller design in hot rolling mill drive system is formulated as

$$\min_{K_a(s)} \left\| \begin{array}{c} W_s(I+GK)^{-1} \\ W_t GK(I+GK)^{-1} \end{array} \right\|_{\infty}. \tag{7}$$

Here, the shaped H^{∞} controller $K_a(s)$ will be designed and then the H^∞ speed controller $K(s)$ is obtained from $K(s) = \alpha(s)K_a(s)$. To design an H^∞ speed controller in (7), the shaped plant $G_s(s)$ is formed by loop shaping technique, frequency weighting functions $W_t(s)$ and $W_s(s)$ are chosen properly, the standard plant $P(s)$ is formed from the closed loop system as shown in Fig. 5, and Glover and Doyle's H^∞ controller design algorithm[2] is used.

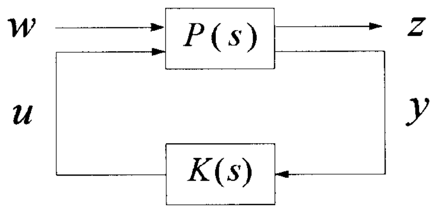


Fig. 6. Standard block diagram for H∞ control.

The standard plant of Fig. 6 from hot rolling mill drive system is expressed as

$$P(s) = \left[\begin{array}{c|c} W_s & -W_sG_s \\ 0 & W_tG_s \\ \hline I & -G_s \end{array}\right] \tag{8}$$

and the state space representation of (8) is transformed into

$$P(s) = \left[\begin{array}{ccc|c|c} a_g & 0 & 0 & 0 & -b_g \\ b_{ws}c_g & a_{ws} & 0 & b_{ws} & -b_{ws}d_g \\ 0 & 0 & a_{wtg} & 0 & b_{wtg} \\ \hline d_{ws}c_g & c_{ws} & 0 & d_{ws} & -d_{ws}d_g \\ 0 & 0 & c_{wtg} & 0 & d_{wtg} \\ \hline c_g & 0 & 0 & I & -d_g \end{array}\right] \tag{9}$$

where, G_s, W_tG_s and W_s are defined as

$$G_s = \left[\begin{array}{c|c} a_g & b_g \\ \hline c_g & d_g \end{array}\right], \tag{10}$$

$$W_tG_s = \left[\begin{array}{c|c} a_{wtg} & b_{wtg} \\ \hline c_{wtg} & d_{wtg} \end{array}\right], \tag{11}$$

$$W_s = \left[\begin{array}{c|c} a_{ws} & b_{ws} \\ \hline c_{ws} & d_{ws} \end{array}\right]. \tag{12}$$

The weighting functions for loop shaping, sensitivity minimization and complementary sensitivity minimization are chosen as

$$\begin{aligned} \alpha(s) &= 0.6s \\ W_s(s) &= \frac{1}{0.26(s+0.001)} \\ W_t(s) &= \frac{s^2+200s+10^4}{3\times10^8}. \end{aligned} \tag{13}$$

Finally, the H^∞ speed controller $K(s)$ for hot rolling mill drive system is obtained as

$$K(s) = \frac{\begin{array}{c} 1468s^9 + (3.444\,\mathrm{E}6)s^8 + (3.143\,\mathrm{E}9)s^7 \\ + (1.471\,\mathrm{E}12)s^6 + (3.881\,\mathrm{E}14)s^5 + (5.33\,\mathrm{E}16)s^4 \\ + (1.781\,\mathrm{E}18)s^3 + (1.885\,\mathrm{E}19)s^2 + (6.093\,\mathrm{E}19)s \end{array}}{\begin{array}{c} s^9 + 2572s^8 + (2.694\,\mathrm{E}6)s^7 + (1.542\,\mathrm{E}9)s^6 \\ + (5.426\,\mathrm{E}11)s^5 + (1.179\,\mathrm{E}14)s^4 + (1.249\,\mathrm{E}16)s^3 \\ + (1.394\,\mathrm{E}17)s^2 + (4.111\,\mathrm{E}17)s + (4.109\,\mathrm{E}14) \end{array}} \tag{14}$$

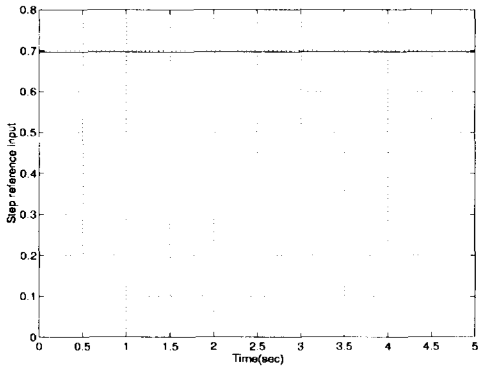
by $K(s) = \alpha(s)K_a(s)$. If the designed controller is not satisfactory, choose another weighting functions and design H^∞ speed controller again using the above controller design procedures.

The speed control performance from the proposed controller is compared with that from the existing PI controller through the computer simulation. Because load torque change is unknown disturbance in real hot rolling process and current sensor gives serious effect to the performance of drive system controller, Load torque disturbance and gain change of current sensor are treated in simulation as disturbance and parameter variation, respectively. And reference speed signals and load torque disturbances are selected as step signals and pulse signals. Then the performance characteristics of over-shoot, steady state error, robustness, and tracking ability are investigated. For reference speed signals, step signal is the typical speed input used in field work and pulse signal is used for analyzing the characteristics in start and stop operation of the drive system. Because the load torque is varied as the change of speed acceleration, step change load torque disturbances are used as test signals. The simulation is on the basis of the hot rolling mill drive system model of Fig. 3. For simulation, the SIMULINK software package is used.

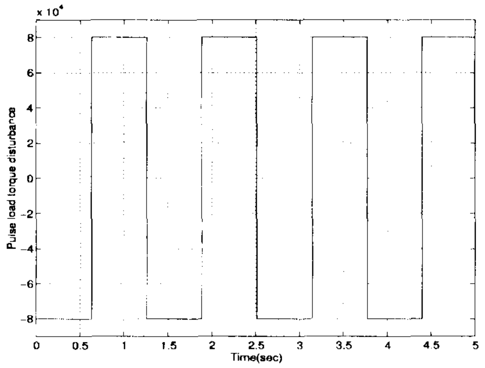
The simulation results from the existing PI speed controller and the designed H^∞ speed controller are shown in Fig. 6 ~ Fig. 8. For step reference speed signal and pulse wave load torque, the H^∞ speed controller has better results of disturbance rejection than the PI speed controller. The overshoot is reduced from 26% to 5.7%. For pulse wave reference speed signal and step change load torque, Fig. 7 shows that the settling time of the H^∞ speed controller is 0.3 second but that of PI speed controller is 1.2 second. So the H^∞ speed controller guarantees wide bandwidth and good tracking performance. And the above two simulation results show that two control methods have small steady state errors. When current sensor gain has 80% value of the original value, the simulation result is shown in Fig. 8. The drive system with PI speed controller is oscillatory but the system with the H^∞ speed controller is converged to reference speed signal. From this design example, it is evident that the proposed H^∞ speed controller has better results than the existing PI controller in guaranteeing good performance and robust stability against parameter variations and disturbances. That is, the H^∞ speed controller guarantees wide bandwidth, small overshoot, good disturbance rejection, and good tracking characteristics in speed control for hot rolling mill drives.

V. Conclusion

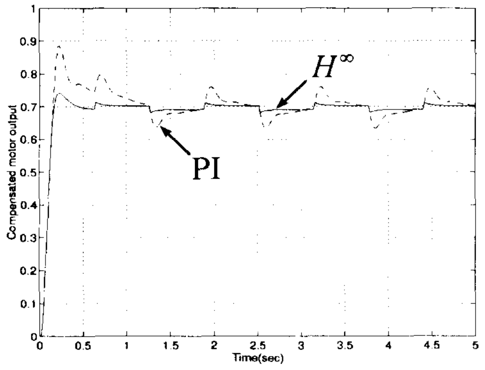
The H^∞ speed controller was designed for hot rolling drives of #2 hot rolling mill of POSCO. For designing an H^∞ speed controller, the full plant model was constructed from the hot rolling mill drive system except speed controller. Using weighted mixed sensitivity H^∞ control problem, sensitivity minimization and robust stability were achieved in speed control to hot rolling mill



(a) Step reference speed signal

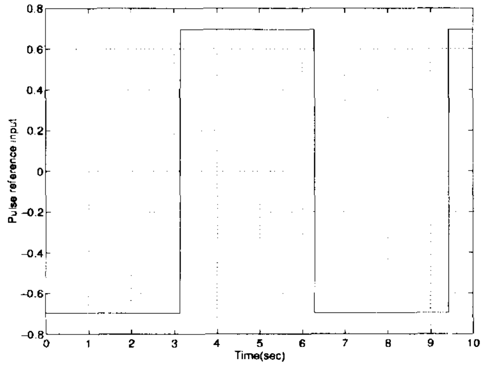


(b) Pulse wave load torque

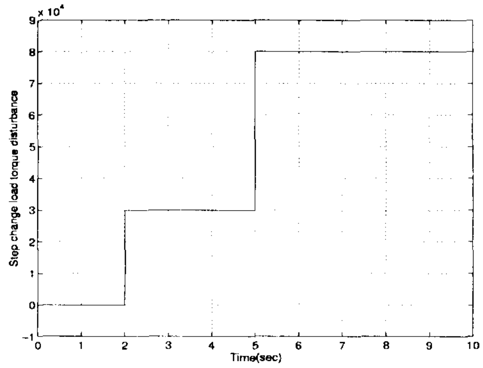


(c) Motor speed response of PI and H^{∞} speed controller

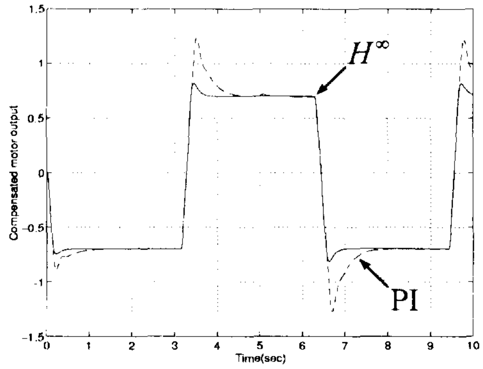
Fig. 7. The speed response of drive system with step reference speed signal and pulse wave load torque.



(a) Pulse wave reference speed signal

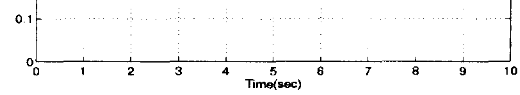


(b) Step change load torque

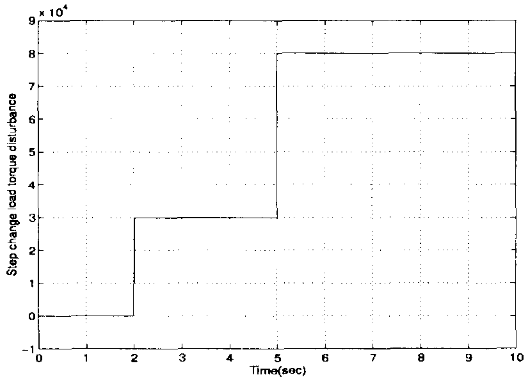


(c) Motor speed response of PI and H^{∞} speed controller

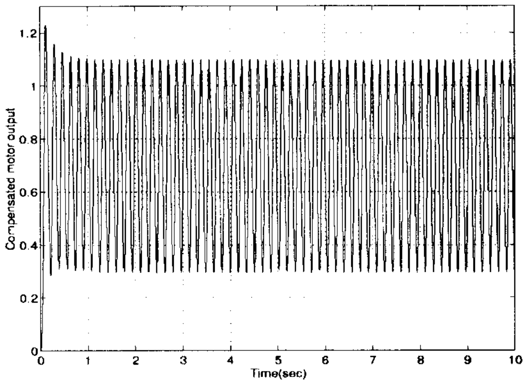
Fig. 8. The speed response of drive system with pulse wave reference speed signal and step change load torque.



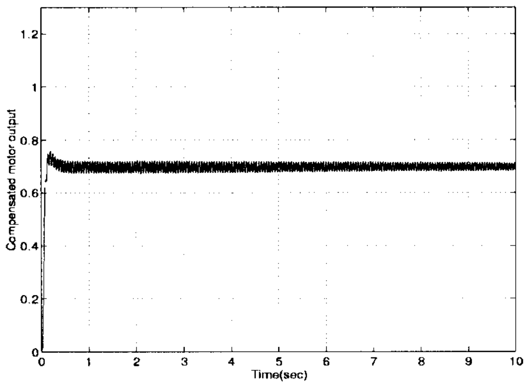
(a) Step reference speed signal



(b) Step change load torque



(c) PI speed controller



(d) H^∞ speed controller

Fig. 9. The speed response of drive system with current sensor gain change.

drives. Through various simulation conditions, it was confirmed that the H^∞ speed controller guaranteed the robust stability of closed loop system against parameter variations and minimized the effects of load torque disturbances. Moreover, the H^∞ speed controller had better performance than the existing PI speed controller in the sense of good tracking, wide bandwidth, and small overshoot. To achieve good performance in field application, the speed signals from all of the hot rolling mill drives must be linked and regulated properly.

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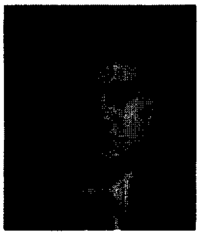

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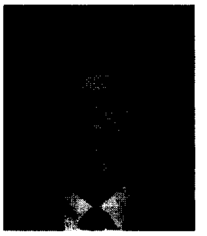

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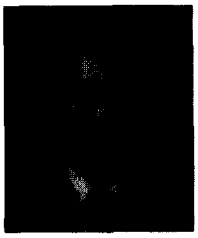

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