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쌍롤형 박판주조기의 모델링과 적응최적제어

Modeling and Adaptive Optimal Control of a Twin Roll Strip Caster

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Abstract: In this paper the modeling and control of a twin roll strip caster is investigated. Mathematical models for the strip casting process are obtained by analyzing five critical areas such that the molten steel level in the pool, solidification process, roll separating force and torque, roll dynamics including hydraulic actuators, and roll drive system. A two-level control strategy is proposed. At lower level, three local subsystems are independently feedback-controlled by suitable local controllers which perform well to the behaviors of each subsystem. They are a variable structure control of the molten steel level in the pool, an adaptive predictive control of the roll gap which is directly related to the strip thickness, and an H^{∞} control of the roll drive system. At higher level, all reference signals to the lower level subsystems are generated by an optimal controller in the perspective of regulating the strip thickness and roll separating force. Simulations are provided.

Keywords: steel, strip casting, feedback control, modeling, rolling mills, decentralized control.

1. Introduction

Strip casting is a new steel-strip production method which casts steel-strip by pouring the molten liquid steel directly into the pool made in between two rotating rolls. It combines the technology of continuous casting and the technology of rolling. The production line from molten liquid steel to final coils can be much shortened by this method. Strip casting technology is currently considered as an emerging new technology together with the COREX process in the steel process industries.

In this paper, the modeling and control of a twin roll strip caster is investigated. For better understanding and systematic investigation the process has been divided into five subparts for modeling, and three subparts for control. The five subparts for modeling are the molten steel level dynamics, the solidification process of the molten steel from the initial contact point with roll surface to the kiss point, the roll separating force and torque relations, the roll gap dynamics including hydraulic actuators, and the roll and DC drive dynamics. The three subsystems for control are a roll gap positioning system, a roll drive system and a molten steel level control system. Two-level control structure, i.e. low level local control and high level optimal control, is proposed. The local controllers include a variable structure control of the molten steel level, an adaptive one step ahead predictive control of the roll gap, and an H_{∞} control of the roll drive system. The reference inputs to each local controllers are provided by a high level optimal controller in terms of regulating the strip thickness and rolling force. Finally a stable startup strategy is suggested and simulation results are provided.

The control issues of the paper are to obtain uniform thickness of the strips and to maintain constant roll separating force throughout the casting in the presence of various disturbances. The contributions of the paper are; i) Strip casting process is systematically analyzed, and mathematical models for the whole process are provided; ii) By localizing control design for each subsystem and synthesizing the reference signals to the subsystems from the perspective of achieving control goals, the control laws for each subsystem are much simplified and better overall performance is achieved; iii) This paper is the first paper proposing an integrated control for the whole strip casting process. It is also noted that each local controller is introduced by incorporating unmodeled dynamics and disturbances.

2. Modeling of Strip Casting Process

Fig.1 shows a schematic diagram of the strip casting process. Molten liquid steel from tundish is poured into the area made by two rotating rolls (drums) and two side dams. The bottom end of the nozzle through which the molten steel comes down is submerged in the pool of the molten steel which is not yet solidified. The amount of molten steel in the pool is controlled by adjusting the height of the stopper. The molten steel is then solidifies rapidly from the outside (roll side) to the inside, and the solid portion becomes thicker as the rolls rotate. The cross point of the two boundary lines separating liquid and solid is called a "kiss point", and the narrowest part of the strip is called a "nip point". The thickness of the strip is controlled by the distance between the two twin rolls, and the overall shape is formed by an electro-hydraulic gap positioning system. The gap positioning system equipped with hydraulic cylinder adjusts the roll gap by translating one roll back and forth which is mounted on a low friction linear bearing. The heat transmitted to the rolls due to solidification is removed by flowing through some cooling liquid inside the rolls.

2.1 Molten Steel Level Dynamics

Let m be the total mass of the steel in the control volume which is defined by the area made by the two rotating drums and two side dams. The change of mass in the control volume is described by the continuity equation as

$$\dot{m} = \dot{m}_i - \dot{m}_o \tag{1}$$

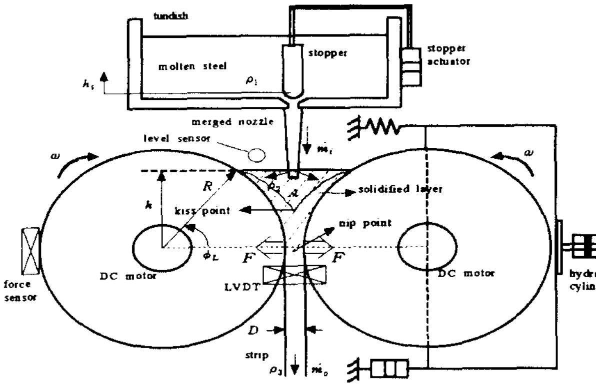


Fig. 1 Strip Casting Process

where subscripts i and o stand for in and out, respectively. Let ϕ_L be the angle between the horizontal line and the line segment heading to the level of molten steel. Let A be the area of the cross section of the control volume. Then from the geometry the following relations are obtained.

$$A = R\left\{(2R+D)\sin\phi_L - \frac{R}{2}\sin(2\phi_L) - R\phi_L\right\}$$

$$m = \rho_2 LA \tag{2}$$

where R and L are the radius and width of the roll. ρ_2 is the average density of the material in the control volume. D is the thickness of strip.

The mass flow rate out of the control volume is given as

$$\dot{m}_o = \rho_3 LRD\omega \tag{3}$$

where ρ_3 is the density of the strip coming out of the control volume and ω is the angular velocity of the roll. And the liquid steel flowing into the volume is described by a 1st order differential equation in which the stopper position is the input to the system as follows

$$\dot{m}_i = \frac{\rho_1 k_q}{\tau s+1} h_s \tag{4}$$

where ρ_1 is the density of the molten steel, and τ and k_q are time constant and gain, respectively.

By combining equations (1), (2), (3), (4) and substituting $h = R\sin\phi_L$, the following differential equation for molten steel level is obtained.

$$\rho_2 L\left\{2R + D - 2R\sqrt{1-\left(\frac{h}{R}\right)^2}\right\}\dot{h} + \rho_2 Lh\dot{D} - \frac{\rho_1 k_q}{\tau s+1} h_s + \rho_3 LRD\omega = 0 \tag{5}$$

2.2 Modeling of Solidification Process

The growth of solidification in Lagrangian description (description is tagged on the particles) can be described in the following equation

$$\delta(T) = C(T-\tau)^{\beta} \tag{6}$$

where $\delta(T)$ is the thickness of the solidified layer, T is the total elapsed time since the molten steel first hit the roll surface, τ is a solidification delay which occurs in case of overheating of the molten steel, and C and β are coefficients determined by experiments. In particular, the thickness of the solidified layer at the kiss point δ_K is given by

$$\delta_K = C(T_K-\tau)^{\beta} \ . \tag{7}$$

On the other hand, if we observe the solidification process in a fixed reference coordinate frame (Eulerian description) the thickness of the solidification layer δ varies in time. Let $\phi_K(t)$ be the angle from the horizontal line to the kiss point at time t. Let $\phi_L(t-T_K)$ be the angle from the horizontal line to the level of pool at T_K ahead of time. Then the following relationship between the roll speed and T_K is obtained. (Bernhard and Rake, 1994)

$$\phi_L(t-T_K) - \phi_K(t) = \int_{t-T_K}^{t} \omega(\tau)d\tau \tag{8}$$

where $\omega(t)$ is the roll rotating speed. And from the geometry in Fig. 2 the following equation between ϕ_K and δ_K is obtained at the kiss point as

$$(R+\delta_K(t))\cos\phi_K(t) = R + \frac{D(t)}{2} \ . \tag{9}$$

We now investigate a differential equation for solidification time

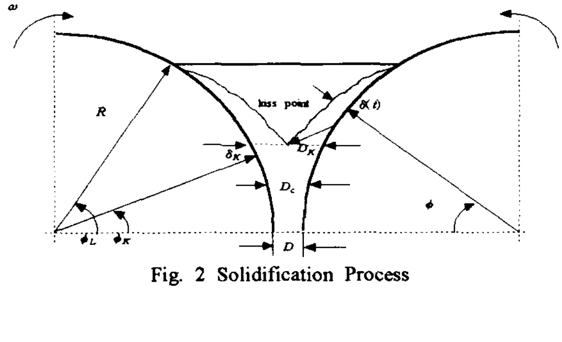


Fig. 2 Solidification Process

$T_K(t)$ to the kiss point. Substituting (7) into (9) yields

$$\{R + C(T_K(t)-\tau)^{\beta}\}\cos\phi_K(t) = R + \frac{D(t)}{2} \tag{10}$$

Assuming that the angle to the kiss point is small, expand $\cos\phi_K$ in the Tayer series up to the second term, then (10) becomes

$$\{R + C(T_K(t)-\tau)^{\beta}\}\left(1 - \frac{\phi_K^2(t)}{2}\right) = R + \frac{D(t)}{2} \ . \tag{11}$$

Differentiating (8) and (11) in time yield

$$\dot{\phi}_L(t-T_K)(1-\dot{T}_K) - \dot{\phi}_K = \omega(t) - \omega(t-T_K)(1-\dot{T}_K) \tag{12}$$

$$C\beta(T_K(t)-\tau)^{\beta-1}\dot{T}_K(t)\left(1-\frac{\phi_K^2(t)}{2}\right) - \{R + C(T_K(t)-\tau)^{\beta}\}\phi_K(t)\,\dot{\phi}_K(t) = \frac{\dot{D}(t)}{2} \tag{13}$$

Combining equations (11)-(13), and skipping the dependence of T_K, ϕ_K and D on t for simplicity, the dynamics of T_K is obtained as

$$\dot{T}_K = \frac{\dot{\phi}_L(t-T_K) - \omega(t) + \omega(t-T_K) + g_2(D, T_K)\dot{D}}{\dot{\phi}_L(t-T_K) + \omega(t-T_K) + g_1(D, T_K)} \tag{14}$$

Once T_K is determined, the position of the kiss point ϕ_K can be decided from (11), and therefore the rolling force can be calculated again from (15) in Section 2.3. It is observed from (14) that three variables ϕ_L, ω, and D play main roles in regulating T_K, and henceforth in regulating the roll separating force F. Therefore, the control objective in Section 3 becomes the regulation of these variables to their desired values in normal operation.

2.3 Roll Separating Force and Torque

Several mathematical equations which describe the generated roll forces and moments in hot rolling are available in the literature. In this paper, we adopt the Ford and Alexander's method (Pietrzyk and Lenard, 1991, pp.62-63) for calculating the roll separating forces and roll torques as follows.

$$F = 1.571\,\bar{k}D_K\left(\sqrt{\frac{Rr}{D_K}} + \frac{R}{D_K}\frac{r}{2-r}\right) \tag{15}$$

and

$$M = Rr\bar{k}D_K\left\{1.571 + \frac{2}{3}\frac{3-2r}{(2-r)^2}\sqrt{\frac{Rr}{D_K}}\right\} \tag{16}$$

where F represents the separating force per unit width, M is the roll torque per unit width for both rolls, $\bar{k}$ is the average shear yield strength in the pass, R is the roll radius, D_K is the strip thickness at the kiss point, and r represents the reduction ratio.

2.4 Roll Gap Dynamics

Fig. 3 shows a roll positioning system equipped with hydraulic actuator, and a DC roll drive system. At the steady state, the characteristics of the hydraulic subsystem with a symmetric servo valve is assumed to be proportional to the servo valve spool position d and the pressure difference $p_l = p_a - p_b$ as

$$q = \alpha_1 d - \alpha_2 p_l \tag{17}$$

where q is the flow from the servo valve to the cylinder, and α_1 and α_2 are proportionality constants. The servo valve spool dynamics, the leakage flow across the valve spool, and the compression of the hydraulic fluid are all neglected. The following equations are obtained for the two rod cylinder as

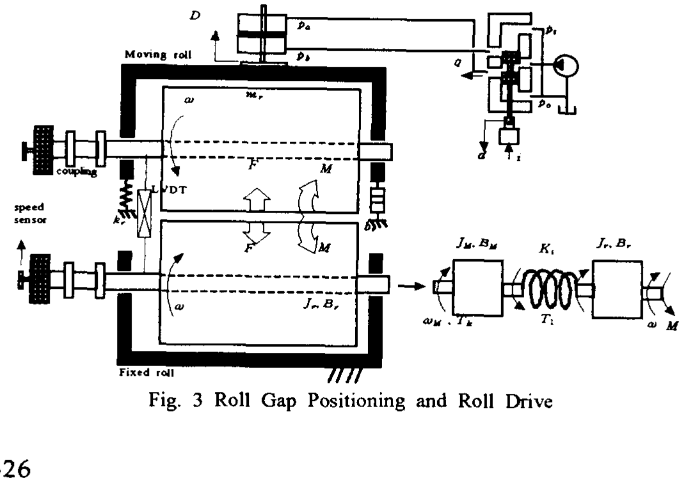


Fig. 3 Roll Gap Positioning and Roll Drive

$$d = K_i i \quad (18)$$

$$q = A_{cyl} \frac{dD}{dt} \quad (19)$$

$$A_{cyl} p_l = m_r \frac{d^2 D}{dt^2} + b_r \frac{dD}{dt} + k_r D + F \quad (20)$$

where i is the input current to the servo valve, A_{cyl} is the cross area of the cylinder. D is the roll gap, m_r, b_r, k_r are the mass, damping and spring coefficient for the moving roll unit, respectively. It is noted that the roll separating force F is a disturbance in (20).

2.5 Roll Drive Dynamics

As shown in the lower right corner of Fig. 4, a torsional vibration can be assumed to exist in the mill drive system because of long gear coupling. In this case the drive system can be modeled as a two mass system with a torsional spring (Miyazaki and Ohishi, 1997).

Since the bandwidth of the current controller is generally much wider than that of speed controller, the current command input can be assumed to be equal to the motor armature current i_a. Then the motor torque T_M is given as

$$T_M = K_T \, i_a \quad (21)$$

where K_T is a torque constant. Hence, the dynamics of the roll drive subsystem is summarized as

$$\begin{aligned} T_M &= J_M \dot{\omega}_M + B_M \omega_M + T_1 \\ T_1 &= K_s(\theta_M - \theta) \\ T_1 &= J_r \dot{\omega} + B_r \omega + M \end{aligned} \quad (22)$$

where J_M and B_M are the inertia and damping coefficient of the motor, K_s is a torsional spring constant, J_r and B_r are the inertia and damping coefficient of the rolls, and M is the roll torque.

3. Process Control Design

The control goal in the paper is to obtain uniform thickness of the strip and to maintain constant roll separating force to minimize residual stresses in the strip. Strip thickness variation results from various causes such that the fluctuation of roll separating forces, the elasticity and the eccentricity of the rolls, and the imprecision of roll gap positioning system. Constant rolling force thus leads to strip of constant thickness.

In this section we propose a two level controller. The low (local) level controller regulates the output of each subsystem by direct feedback, and runs independently in robust fashion. The effects from other subsystems are incorporated by adjusting the reference signals to each subsystem during operations. The higher level controller assigns desired reference values to each lower level controller in the perspective of achieving optimal performance during the startup operation, and then maintain them as constants afterward. Fig. 4 shows the concept of the proposed control design. For the entire system the regulated variables are the strip thickness D and rolling force F. The system inputs are the

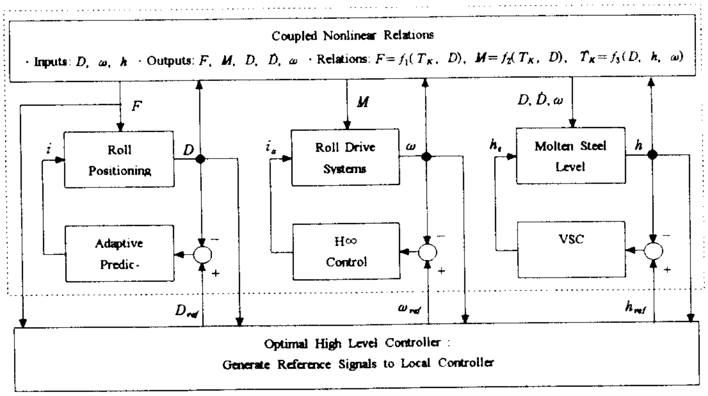


Fig. 4 Structure of Decentralized Controls with Supervisory Inputs

stopper height h_s, the servo-valve current i, and the armature current i_a to the motor.

3.1 Local Controllers

The whole control system is divided into three subparts: the molten steel level control, the roll gap control, and the roll speed control. The signals used for feedback are the height of molten steel, the speed of the rolls, the roll gap, and the roll separating force. In the following subsections, three low level control designs for the subsystems are introduced.

3.1.1 Molten Steel Level Control

From equations (3)-(5) the following nonlinear equation for the molten steel level h is obtained.

$$\dot{h} = f(h, D, \dot{D}, \omega) + b(h, D) h_s \quad (23)$$

where, h_s is the stopper height.

Observing the above equation, several issues can be recognized as potential impediments to tighten desired molten level. i) Nonlinearities: The process contains nonlinearities because of the geometry of the roll and the casting speed. ii) Time-varying: The submerged valve end and the stopper tend to clog and their sizes may change due to wear or erosion, and hence k_q and τ is time-varying. iii) Uncertainties and disturbance: ρ_2 can not be obtained by sensing, and it is also time-varying. The oscillation of the molten steel in tundish affects k_q and τ. iv) Time delay: The control input gain $b(\cdot)$ may contain some time delay.

In this subsection, a sliding mode control technique for the level control is proposed to overcome the above problems. Sliding mode control technique is known to be very effective to handle parameter and modeling uncertainties. It further provides robustness in the presence of disturbances. The following procedure is summarized.

First in order to have the system to track $h(t) = h^d(t)$, where $h^d(t)$ is the desired level, the following sliding surface ($s = 0$) and sliding condition are defined (Slotine and Weiping, 1991).

$$\tilde{h} = h - h^d, \quad s = \left(\frac{d}{dt} + \lambda\right) \int_0^t \tilde{h} d\tau \quad (24)$$

$$\frac{1}{2} \frac{d}{dt} s^2 \le -\eta \, |s| \quad (25)$$

where τ and η are strictly positive constants. To achieve the sliding mode of (25) and to handle undesirable chattering, the following reaching law is used.

$$\dot{s}(t) = -k sat\left(\frac{s}{\Phi}\right) \quad (26)$$

where Φ is a boundary layer thickness and sat is the saturation function. So the control law is determined from (24) and (26) as

$$h_s = \frac{1}{\hat{b}}\left\{-\hat{f} + \dot{h}^d - \lambda \tilde{h} - k sat\left(\frac{s}{\Phi}\right)\right\} \quad (27)$$

Note that the dynamics f and b are not exactly known, but are estimated as $\hat{f}$ and $\hat{b}$, respectively. Here, we can assume that the estimation error on f is bounded by some known function F as

$$|\hat{f} - f| \le F \,. \quad (28)$$

The bounds of the control gain b is given as

$$0 < b_{min} \le b \le b_{max} \,. \quad (29)$$

Then k must verify the following condition in order to satisfy (25).

$$k \ge |\hat{b}b^{-1}f - \hat{f} + (\hat{b}b^{-1} - 1)(-\dot{h}^d + \lambda \tilde{h})| + \eta \hat{b} b^{-1} \quad (30)$$

3.1.2 Roll Gap Control

Taking the Laplace transform of equations (17)-(20) the transfer function from the armature current i and roll force F to the roll gap D is given by

$$D(s) = \frac{\frac{\alpha_1}{\alpha_2} A_{cyl} K_i}{m_r s^2 + (b_r + \frac{A_{cyl}^2}{\alpha_2}) s + k_r} i(s) - \frac{A_{cyl}}{m_r s^2 + (b_r + \frac{A_{cyl}^2}{\alpha_2}) s + k_r} F(s) \quad (31)$$

We now convert (31) in the discrete form as follows.

$$D(z) = \frac{b_0 z}{z^2 + a_1 z + a_2} i(z) - \frac{c_0}{z^2 + a_1 z + a_2} F(z) \quad (32)$$

Rearranging terms in (32) the following regression form is obtained.

$$D(t) = [\,a_1 \;\; a_2 \;\; b_0 \;\; c_0\,]\begin{bmatrix} -D(t-1) \\ -D(t-2) \\ i(t-1) \\ -F(t-1) \end{bmatrix} = \theta^T\phi(t) \tag{33}$$

Here, the recursive least square estimation algorithm with exponential forgetting for time varying parameters is used to estimate θ^T. (Astrom and Wittenmark, 1995, p.53)

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)(D(t) - \phi^T(t)\hat{\theta}(t-1))$$

$$K(t) = P(t)\phi(t) = P(t-1)\phi(t)(\lambda I + \phi^T(t)P(t-1)\phi(t))^{-1} \tag{34}$$

$$P(t) = (I - K(t)\phi^T(t))P(t-1)/\lambda$$

where λ is a forgetting factor. Finally, with the estimated parameter $\hat{\theta}$, and the desired roll gap $D^d(t+1)$, the following control input is proposed.

$$i(t) = \frac{b_0}{b_0^2 + \lambda}\{D^d(t+1) + a_1 D(t) + a_2 D(t-1) + c_0 F(t)\} \tag{35}$$

3.1.3 Roll Drive Control

In this subsection a robust control for regulating the roll speed and suppressing the torsional vibration of the two mass and spring system is suggested. Following the work of (Ohishi et al., 1996) disturbance observer and coprime factorization are suggested.

From (21)-(22), the following transfer function is obtained.

$$\omega_M(s) = \frac{(\frac{K_T}{J_M}s^2 + \frac{B_L K_T}{J_M J_r}s + \frac{K_s K_T}{J_M J_r})i_a(s) - K_s M(s)}{s^3 + (\frac{B_M}{J_M} + \frac{B_r}{J_r})s^2 + (\frac{B_M B_r}{J_M J_r} + \frac{K_s}{J_M R_g^2} + \frac{K_s}{J_r})s + \frac{B_M K_s}{J_M J_r} + \frac{K_s B_r}{J_M J_r R_g^2}} \tag{36}$$

In order to design a robust servo system, a nominal dynamics $\hat{P}(s)$ using the coprime factorization is defined as.

$$\hat{P}(s) = C(sI - A)^{-1}B = \frac{N(s)}{D(s)} \tag{37}$$

where $N(s), D(s)$ are the coprime factorization of $\hat{P}(s)$. They must be stable and proper functions, which is designed by the state feedback gain matrix F and the state observer gain matrix H defined as

$$\begin{aligned} N(s) &= C(sI - A + BF)^{-1} \\ D(s) &= I - F(sI - A + BF)^{-1}B \\ X(s) &= I - F(sI - A + HC)^{-1}B \\ Y(s) &= F(sI - A + BF)^{-1}H \end{aligned} \tag{38}$$

The following compensators $C_1(s)$ and $C_2(s)$ are determined by the coprime factorization $N(s)$, $D(s)$, $X(s)$, $Y(s)$ and the free parameters $Q(s)$, $K(s)$ as follows

$$C_1(s) = \frac{X(s) + Q(s)N(s)}{Y(s) - Q(s)D(s)} \tag{39}$$

$$C_2(s) = D(s)K(s) + C_1(s)\{N(s)K(s) - 1\}.$$

Further developments are referred to (Ohishi et al., 1996).

3.2 Higher Level Supervisory Control

The input-output relationship of the molten steel level subsystem can be reconfigured for the design of high level controller as in Fig. 5. The other two subsystems can be also reconfigured similarly. Now define the state variables, input variables, and output variables as follows.

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} \equiv \begin{bmatrix} h \\ \omega \\ T_K \\ D \\ \dot{D} \end{bmatrix}, \; \underline{u} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \equiv \begin{bmatrix} h_{ref} \\ \omega_{ref} \\ D_{ref} \end{bmatrix}, \; \underline{y} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \equiv \begin{bmatrix} F \\ D \end{bmatrix} \tag{40}$$

Then the whole three subsystems in Section 3 can be written in compact form as follows.

$$\dot{\underline{x}} = f(\underline{x}, \underline{u}, t) \tag{41a}$$

$$\underline{y} = g(x_3, x_4, t) \tag{41b}$$

where $f: R^+ \times R^5 \times R^3 \to R^5$, $g: R^+ \times R^2 \to R^2$. Linearize (41a,b) around an operating point as follows.

$$\begin{aligned} \dot{\underline{x}} &= A(t)\underline{x} + B(t)\underline{u} \\ \underline{y} &= C(t)\underline{x} \end{aligned} \tag{42}$$

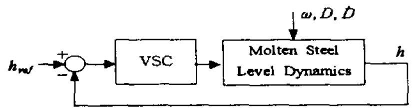


Fig. 5 Reconfigured Input-Output Relationship of Level

where $a_{ij}(t) = \frac{\partial f_i}{\partial x_j}$, $b_{il}(t) = \frac{\partial f_i}{\partial u_l}$, $c_{mn}(t) = \frac{\partial g_m}{\partial x_n}$,

$i, j = 1, 2, \ldots, 5$, $l = 1, 2, 3$, $m = 1, 2$, and $n = 3, 4$.

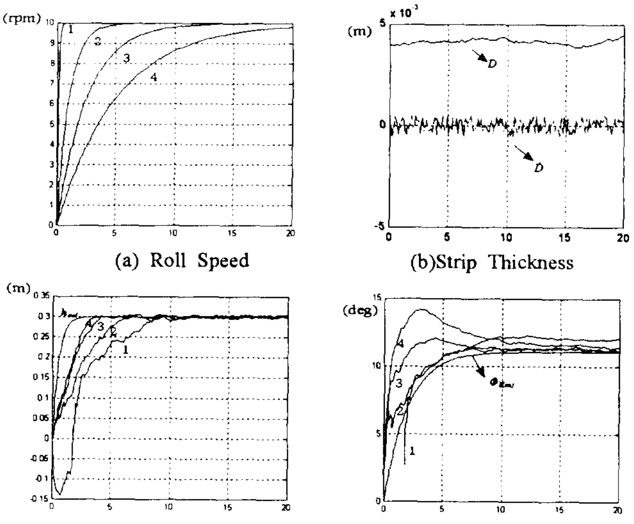
The optimal reference inputs to the subsystems are now obtained by minimizing the performance index defined as

$$J = \tilde{\underline{y}}(t_f)Q\,\tilde{\underline{y}}^T(t_f) + \int_{t_i}^{t_f} \tilde{\underline{y}}\,R\,\tilde{\underline{y}}^T\,dt \tag{43}$$

where $\tilde{\underline{y}} = \underline{y}^d - \underline{y}$ in which $\underline{y}^d$ is the desired values of the output.

4. Simulations

Regulation performance of the molten steel level during the startup process for given strip thickness and roll speeds has been simulated. Four different roll speeds are given as in Fig. 7(a). The corresponding molten steel levels are shown in Fig. 7(c). Considering both the angle of the kiss point and molten steel level, the roll speed number 2 would be appropriate.



(a) Roll Speed (b)Strip Thickness

(c) Molten Steel Level (d)Angle of Kiss Point

Fig. 6 Simulations

5. Conclusions

In this paper the modeling and control of a strip caster was investigated. Mathematical models for strip casting process were obtained by analyzing five critical areas. The control problem was to obtain uniform thickness of the strip, and to maintain constant roll separating force. Two level control strategies were proposed:. The reference signals to each local systems were generated by the higher level optimal controller from the perspective of regulating the roll gap and roll separating force.

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