CONTROL OF THE MOLTEN STEEL LEVEL IN A TWIN ROLL CASTING PROCESS

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Abstract— This paper presents a control strategy to regulate the molten steel level of a strip-casting process. The aim of the process is to produce a solidified strip of constant thickness given by the roll gap under a constant roll separation force. The molten steel level may be controlled using the tundish output flow or the casting speed. However, the casting speed is usually used to control the roll force separation. To improve the strip thickness uniformity we propose the introduction of an intermediary tundish submerse into the pool between the rotating rolls. The molten steel level is thus controlled by the intermediary tundish output flow. Conventional PI, feedback linearizing plus a fuzzy control term and a fuzzy controller in a cascade configuration are considered. Simulation results are presented considering the real system parameters.

Key Words— Strip-casters, twin roll, feedback linearization, supervisory control, fuzzy control.

1 Introduction

The twin roll strip-casting process belongs to a new generation of casting processes, the called near-net-shape processes. The twin roll strip-casting process was first conceived by Henry Bessemer in the middle of last century (Cook *et al.*, 1995; Shin *et al.*, 1995).

A twin roll casting process is essentially a two rolling mill equipped with three main control loops: the molten steel level control loop, the separation force control loop and the casting speed control loop. The molten steel level along with the separation force are considered the most critical to the production of high quality steel strips. In Lee *et al.* (1996) an adaptive fuzzy controller for the molten steel level in a strip-casting process is proposed. They use the inflow rate as the control input. However, the feeding of the molten steel into the pool formed between the two rotating rolls is a source of disturbance in the molten steel level. In this paper we consider the use of an intermediary tundish submerse into the pool to reduce the steel level fluctuations (Tavares and Guthrie, 1998) and we use its level as the control input. The intermediary tundish consists of a refractary recipient with holes to direct the molten steel to the pool formed between the two rotating rolls.

A strip-caster pilot plant installed at IPT São Paulo is shown in Figure 1. The main control units are the mill drive, the cooling and the coiler control units (Santos *et al.*, 2000). The plant is equipped with a set of Programmable Logic Control (PLC) units to perform the measurements and control.

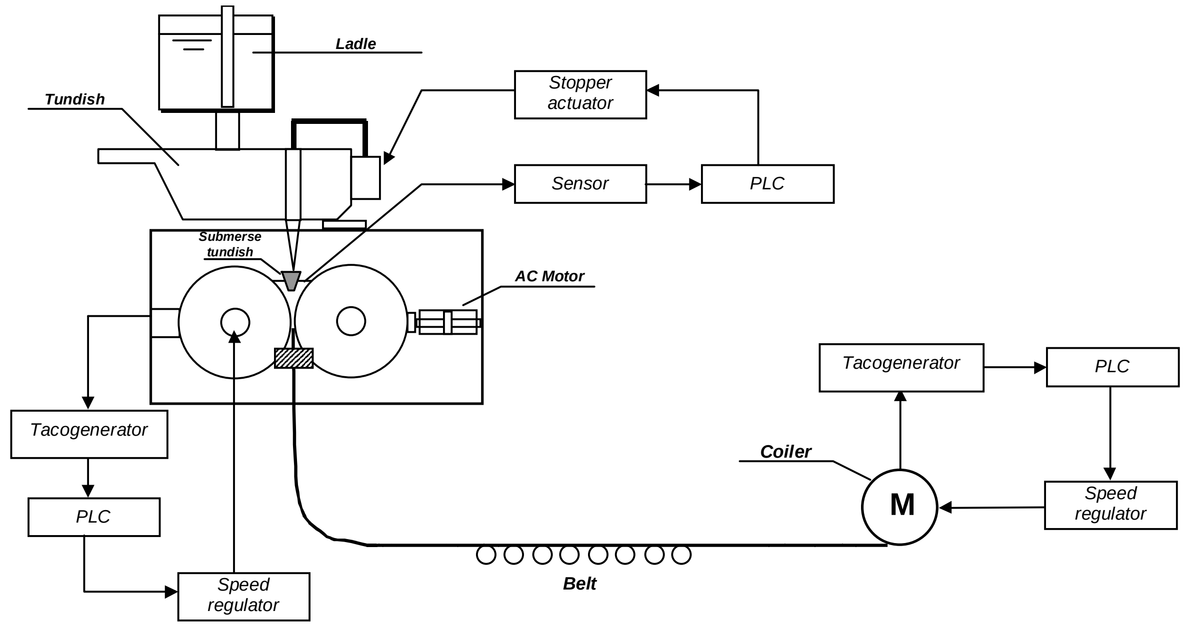

Figure 1. Schematic layout of the strip-caster pilot plant installed at IPT São Paulo.

The present work is organized as follows. In Section 2 the strip-caster modeling for control of the molten steel level between the twin roll is described. Section 3 presents different control strategies for the molten steel level. Finally, in Section 4 simulation results are presented considering the real system parameters.

2 System Modeling

The molten steel level system may be described as a nonlinear system based on the continuity equation of the steel flow and on the Bernoulli equation. Figures 2 and 3 show the geometry of the complete flow system.

2.1 *Intermediary Tundish Molten Steel Level*

The dynamic model of the steel level in the intermediary tundish for input flow rate Q_i and output flow rate Q_{o1} is given as

$$\frac{dh_1}{dt} = \frac{1}{A_T}(Q_i - Q_{o1}) \qquad (1)$$

where $Q_i = c_f d$; $Q_{o1} = k\sqrt{h_1}$, with h_1 and A_T the steel height and area of the intermediary tundish, respectively; c_f the flow coefficient, d the actuator position; $k = n_f A_f \sqrt{2g}$, A_f the area of the holes, $A_f = \pi r^2$, n_f and r the number and radius of the holes and g the acceleration due to gravity (Franklin *et al.*, 1994).

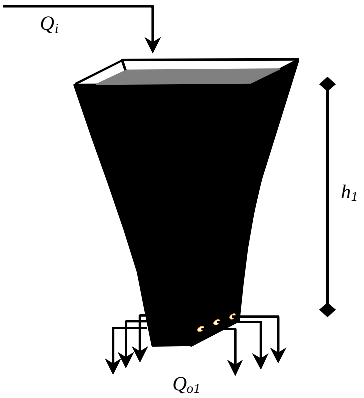

Figure 2. Submerse intermediary tundish.

2.2 *Mill Drive Molten Steel Level*

The dynamic model of the input Q_{o1} and output flow Q_{o2} in the mill drive is described as

$$Q_{o1} - Q_{o2} = \frac{dV}{dt} \tag{2}$$

where V is the volume of the molten steel formed between the rolls, Q_{o2} the output flow from the rolls and Q_{o1} the inflow from the intermediary tundish. The volume V is $2SL$, with S the shaded area as showed in Figure 3 and L the roll length.

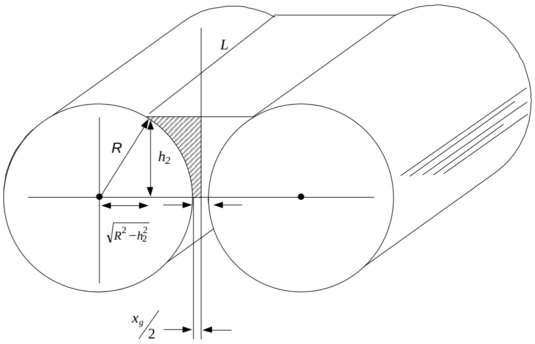

Figure 3. Schematic of the steel level in the mill drive.

The area S can be calculated as

$$S = \int_0^{h_2} \left[\left(\frac{x_g}{2} + R \right) - \sqrt{R^2 - \tau^2} \right] d\tau \tag{3}$$

with R the cylinder radius, x_g the roll gap which determines the desired strip thickness and h_2 the height in [0 R].

Using (3) we may write

$$\frac{dV}{dt} = \left[(x_g + 2R) - 2\sqrt{R^2 - h_2^2} \right] L \frac{dh_2}{dt} \tag{4}$$

and this yields

$$\frac{dh_2}{dt} = \frac{1}{M(x_g, h_2)} [Q_{o1} - Q_{o2}] \tag{5}$$

where

$$M := \left[(x_g + 2R) - 2\sqrt{R^2 - h_2^2} \right] L \text{ and } Q_{o2} = L x_g v_r ,$$

with v_r the casting speed.

In the space state form we have

$$\dot{h} = \begin{bmatrix} \dfrac{-k\sqrt{h_1}}{A_T} \\ \dfrac{[k\sqrt{h_1} - Q_{o2}]}{M(h_2)} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{A_T} \\ 0 \end{bmatrix} Q_i . \tag{6}$$

3 Nonlinear Molten Steel Level Control

The molten steel level between the twin rolls may be regulated using as control input the inflow Q_i or the casting speed v_r. However, the casting speed v_r is usually used to control the roll separation force due to the system constraints. Therefore, as we introduced an intermediary tundish, here the molten steel level control is pursued by controlling the level of the intermediary tundish with an inner control loop for the stopper actuator using a servo-valve. The purpose of the inner control loop is to avoid abrupt changes in the valve position.

The inclusion of the intermediary tundish is very important to the quality of the final product, as it is detailed in Section 1. However, due to its inclusion the molten steel level in the intermediary tundish needs to be monitored and considered in the controller to avoid possible over flow, guaranteeing a good working condition of the process.

In this section the method of input-state linearization by feedback and the fuzzy logic technique are used to regulate the molten steel level at the desired value y_d (Slotine and Li, 1991). In the method of feedback linearization, the nonlinearities in the nonlinear system are canceled to yield a closed-loop linear system.

3.1 *Feedback Linearization Control Strategy*

Assuming in (6) that x_g, h_1, and h_2 are measured, a control law

$$Q_i = \alpha(h) + \beta(h) v \tag{7}$$

with $\alpha : \Re^2 \to \Re$, $\beta : \Re^2 \to \Re$ and v an equivalent control, can be found so that the nonlinear system dynamics is transformed into an equivalent linear dynamics of a simpler form (Slotine and Li, 1991). Based on the equivalent linear system, a tracking controller for the level h_2 can be obtained. We define the error $e := y - y_d$, with $y := h_2$. To guarantee $e \to 0$ as $t \to \infty$ a control term called supervisory control u_s, is added to Q_i .

The supervisory control is of the form $u_S := A \text{ sgn}(e)$, with sgn being the sign function and A a design parameter. The term supervisory control is inspired in the variable structure with sliding mode technique (Slotine and Li, 1991; Wang, 1994).

Moreover, in order to compensate modeling errors that inevitably exist in the strip-casting system, a fuzzy control term u_c is added to Q_i in (7). In the next section we present in detail the development of the fuzzy control term u_c. In addition for comparison purpose, to regulate the molten steel level a fuzzy logic controller in a cascade configuration is presented.

3.2 Fuzzy Control

A fuzzy control law is used as an alternative to control the steel level. The fuzzy logic system used in the fuzzy control term and cascade fuzzy control is formulated using the Mamdani's method, that has been successfully applied to a variety of industrial processes and consumer products (Wang, 1994).

The fuzzy control term is formed by two input fuzzy sets, error e, and error derivative $\dot{e}$, and one output fuzzy set, the modeling error whereas the cascade fuzzy controller is formed by three input fuzzy sets, error e, error derivative $\dot{e}$ and molten steel level in the intermediary tundish h_1, and one output fuzzy set, the stopper actuator input voltage. The fuzzy control term and cascade fuzzy controller use the singleton fuzzifier, the center average defuzzifier, the product inference rule and a fuzzy rule base, which consists of a collection of fuzzy IF-THEN rules of the following form.

Fuzzy control term
R(l):
IF e is M_1^ℓ and $\dot{e}$ is M_2^ℓ
THEN b is K_1^ℓ with confidence degree $\beta_{123} \in [0,1]$

Cascade fuzzy controller
R(l):
IF e is F_1^ℓ, $\dot{e}$ is F_2^ℓ and h_1 is F_3^ℓ
THEN d is G_4^ℓ with confidence degree $\alpha_{1234} \in [0,1]$

where
$\ell = 1,\ 2,\ ...,\ r$ are the number of linguistic rules;
M_1^ℓ, $M_2^\ell, F_1^\ell, F_2^\ell$ and F_3^ℓ are the input fuzzy sets;
K_1^ℓ and G_4^ℓ are the output fuzzy sets;
$(\mathrm{e}, \dot{e}) \in U_y$, $b \in H_b$, $h_1 \in V_{h_1}$ and $d \in R_d$

with U_y , H_b , V_{h_1} , R_d input and output linguistic variables given by

$$U_y := [-\delta_y, +\delta_y] \subset R^2,\ \delta_y > 0\ ,$$
$$H_b := [-\delta_b, +\delta_b] \subset R,\ \delta_b > 0,$$
$$V_{h_1} := [-\delta_{h_1}, +\delta_{h_1}] \subset R,\ \delta_{h_1} > 0,$$
$$R_d := [-\delta_d, +\delta_d] \subset R,\ \delta_d > 0\ ,$$

In the cascade fuzzy controller, U_y and V_{h_1} are universes of discourse, the fuzzy relation R_d is a fuzzy set in the product space U_y x V_d ; that is, R_d is the fuzzy relation induced by the rules with membership function of triangular type and membership grade given by $\mu_R(u,v)$ where $u \in U_y$ and $v \in V_d$.

When no rule involves the association of the input linguistic terms, F_1^ℓ, F_2^ℓ and F_3^ℓ with the output G_4^ℓ, the coefficient α_{1234} is simply assigned to zero. The fuzzy relation can be directly evaluated by

$$\mu_R(F_1^\ell, F_2^\ell, F_3^\ell, G_4^\ell) = \alpha_{1234}\ . \qquad (8)$$

Equation (8) can be illustrated by the following statement: the strength of the relationship that links the linguistic terms $F_1^\ell, F_2^\ell, F_3^\ell$ and G_4^ℓ is equal to the degree of confidence of the rules

R(l):
IF e is F_1^ℓ, $\dot{e} = -\dot{y}$ is F_2^ℓ and h_1 is F_3^ℓ
THEN d is G_4^ℓ.

The same reasoning can be used for the fuzzy control term u_c where H_b is the fuzzy relation induced by the rules with membership function $\mu_H(u)$ as in (8).

The fuzzy logic system adopted is presented in Figure 4 and the molten steel level basic control configuration with the fuzzy control term is shown in Figure 5.

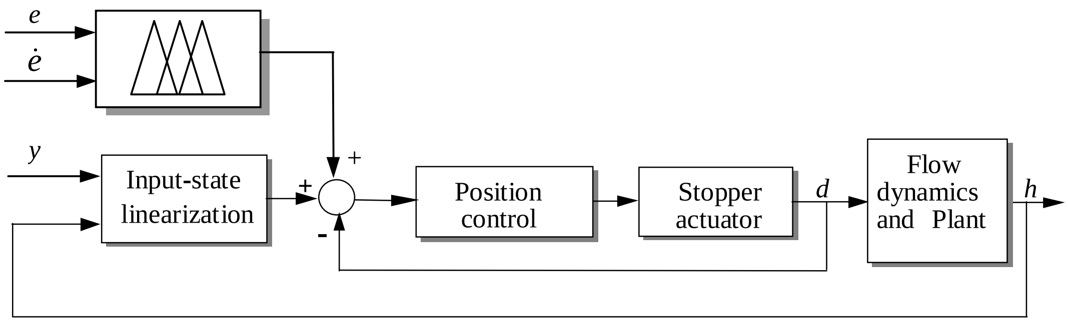

Figure 4. Schematic of the fuzzy logic control system.

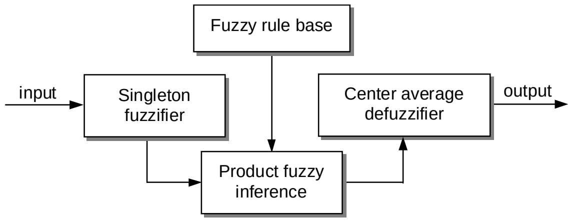

Figure 5. Schematic of the steel level control unit.

4 Simulation Results

In this section, results of simulations are presented for a PID controller, a feedback linearization controller and a cascade fuzzy controller. All results were obtained considering the stopper actuator dynamics. The radius and width of the roll cylinders are both 0.375[m]. The molten steel levels in normal operation are: $y_d = 0.13[m]$, $y_{\min} = 0.12[m]$, $y_{\max} = 0.14[m]$ and the nominal inflow is $Q_{o2} = 3.07e-3[m^3/s]$ which is in accordance with the design of the intermediary tundish. The desired values of gap and level are set as 0.002[m] and 0.13[m], respectively. The proportional plus integral and derivative gains of the conventional PID controller are set as 50, 4.5 and 100, respectively.

In the design of the cascade fuzzy control law, we used seven linguistic rules (*r=7*) to the input fuzzy sets, error e, error derivative $\dot{e}$ and three linguistic rules (*r=3*) to the input fuzzy set, the molten steel level in the intermediary tundish. The latter is needed to avoid possible over flow. For the output fuzzy set, the stopper actuator input voltage, we used seven linguistic rules (*r=7*).

In the design of the fuzzy control term added to the feedback linearization controller, we used three linguistic rules to both input and output fuzzy sets.

Figure 6 shows the system responses to a step reference for the molten steel level when the desired molten steel level is chosen as 0.13 m. Outflow Q_{o2} and roll speed disturbances as well as model errors are considered in the simulations. In Figure 6 a 10% outflow Q_{o2} disturbance is introduced after 50s.

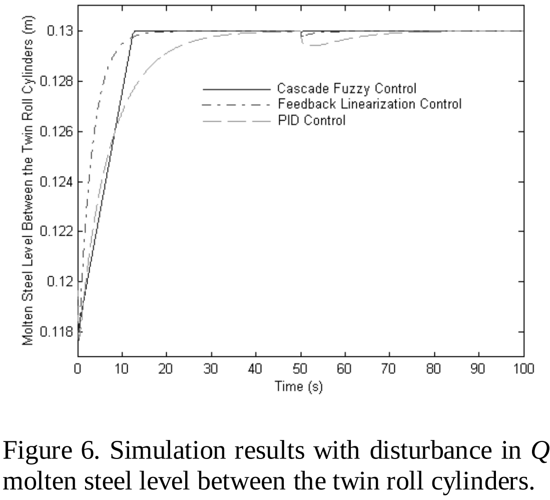

Figure 6. Simulation results with disturbance in Q_{o2} - molten steel level between the twin roll cylinders.

Figure 7 shows results for a roll angular speed disturbance of 10% containing up to the third harmonics on its operating amplitude. Clearly, the simulation results show the superiority performance of the fuzzy controller.

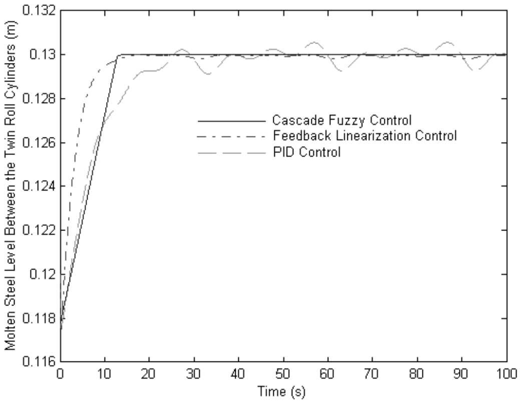

Figure 7. Simulation results with roll angular speed disturbance containing up to the third harmonics - molten steel level between the twin roll cylinders.

Figure 8 shows results for gap disturbance of about 10% around the desired roll gap and containing up to the third harmonics (Lee. *et al*).

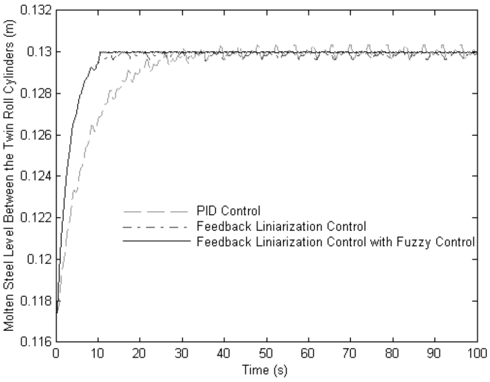

Figure 8. Simulation results for the molten steel level between the twin roll cylinders with disturbance in the roll gap

Both the feedback linearization control and PID control showed inefficient to cancel the modeling errors in the roll gap and the cascade fuzzy controller did not work with modeling errors.

5 Conclusion

In this work nonlinear control strategies for the molten steel level in a strip-caster plant installed at the IPT São Paulo is proposed. Different control strategies are explored in order to achieve a high performance regulation. The simulation results show the superiority performance of the feedback linearization controller with fuzzy control term for compensation modeling errors as compared to conventional PI, feedback linearization and cascade fuzzy controller. An important feature of the fuzzy controller is its flexibility to consider the controller design constraints in the process and control variables. Since the aim of the process is to produce a solidified strip of constant thickness under a constant roll separation force, the main control unit of the strip-caster system are a nonlinear coupled system and this will be considered in future work.

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