Hybrid Control Design for Twin-Roll Strip Casting

N. S. D. Arrifano, R. R. Nascimento, J. Santos, V. A. Oliveira, E. Gesualdo
Departamento de Engenharia Elétrica
USP São Carlos
CP 359, CEP 13560-970
São Carlos, SP, Brazil
Tel. : 55-162739336
Fax : 55-162739372
e-mail: vilmao@sel.eesc.sc.usp.br

J. P. V. Tosetti
Instituto de Pesquisas Tecnológicas do Estado de São Paulo S.A.
DIMET, Divisão de Metalurgia
São Paulo, SP, Brazil

Abstract

This paper presents a control strategy to regulate the molten steel level of a strip-casting process. The molten steel level may be controlled using the roll gap, the tundish output flow or the roll rotation speed as control inputs. To improve the strip thickness uniformity the molten steel level we propose the use of the roll rotation speed as the control input assuming the tundish output flow is regulated in a previous stage. To regulate the molten steel level, conventional PI and feedback linearizing controllers with compensation for modeling errors are considered. Simulation results are presented considering the real system parameters.

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 [1] and [2]. A twin roll casting process is essentially a two rolling mill equipped with three main control loops: the molten steel level control loop, the roll gap control loop, and the force control loop. The molten steel level is considered the most critical to the production of high quality steel strips. In [3] an adaptive fuzzy controller for the molten steel level in a strip-casting process is proposed. They use the inflow 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. The steel level fluctuations may be reduced by adding an intermediary tundish submerse into the pool and using the roll rotation speed as the control input [5].

A pilot strip-caster 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 [5].

The present work is organized as follows. In Section 2 the strip-caster model for molten steel level control is described. Section 3 presents the control strategy for the molten steel level. In Section 4 results of simulation are presented and Section 5 concludes the paper.
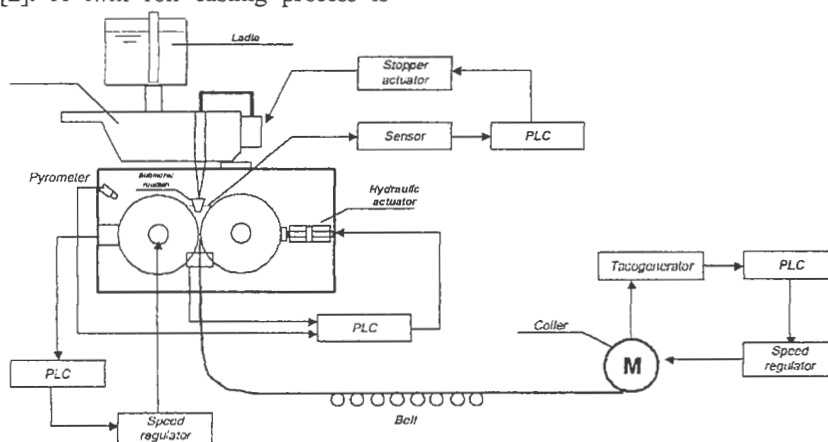

Figure 1. Schematic layout of the strip-caster pilot plant installed at IPT São Paulo.

2. Molten Steel Level Model for Control

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. Several types of disturbances and uncertainties may occur in the molten steel level system such as inflow change and roll eccentricity [3]. Figure 2 shows the geometry of the mill drive unit. Following, we present a description of the molten steel level system.

The dynamic model of the input and output flow in the mill drive is described as

$$Q_i - Q_o = \frac{dV}{dt} \qquad (1)$$

where V is the volume of the molten steel formed between the rolls; Q_o the output flow from the rolls and Q_i the inflow from an intermediary tundish. The volume V is $2SL$ with S the shaded area showed in Figure 2 and L the roll length. The area S can be calculated as

$$S = \int_0^y \left[\left(\frac{x_g}{2} + R \right) - \sqrt{R^2 - y^2} \right] dy \qquad (2)$$

with R the cylinder radius; x_g the roll gap and y the level height in $[0\ R]$.

Using (2) we may write

$$\frac{dV}{dt} = \left[(x_g + 2R) - 2\sqrt{R^2 - y^2} \right] L \frac{dy}{dt} \qquad (3)$$

and this yields

$$\frac{dy}{dt} = \frac{1}{M(x_g, y)} \left[Q_{in} - Q_{out}(x_g, v_r) \right] \qquad (4)$$

with $\qquad M := \left[(x_g + 2R) - 2\sqrt{R^2 - y^2} \right] L \qquad$ and $Q_{out}(x_g, v_r) = L x_g v_r$.
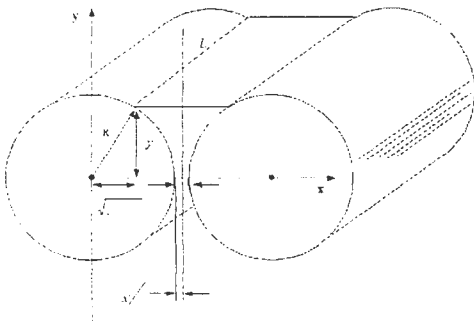

Figure 2. Schematic of the steel level control unit.

3. Nonlinear Molten Steel Level Control

The molten steel level may be regulated using as control input the gap between the rolls x_g, the inflow Q_i or the roll rotation speed v_r. However, the gap x_g and the inflow Q_i are regulated variables due to the system constraints. Therefore, here the molten steel level control is pursued by choosing the roll rotation speed v_r as the control input and including an inner control loop for the speed regulation of a DC motor used in the roll driving. The purpose of the inner control loop is to avoid abrupt changes in the DC motor speed. The molten steel level control configuration diagram is shown in Figure 3.
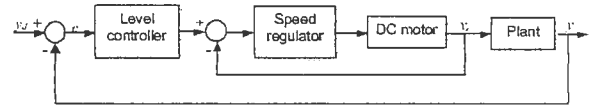

Figure 3. Schematic of the steel level control unit.

In this section the method of feedback linearization with compensation for modeling errors is used to regulate the molten steel level at the desired value y_d [6]. In the method of feedback linearization, the nonlinearities in a nonlinear system are canceled to yield a closed-loop linear system. The compensation for modeling errors is accomplished by including a fuzzy control law.

3.1. Feedback Linearization Control Strategy

Assuming in (4) that x_g is measured and that Q_i and the function $M(y)$ are known, a control law v_r^* would be of the form

$$v_r^* = \frac{1}{L x_g} \left[-M(y) K_p e + Q_i \right] \qquad (5)$$

where K_p is a design parameter. The error $e := y_d - y$, is thus given by

$$e(t) = e(0) \exp(-K_p t) \qquad (6)$$

as substituting v_r^* in (4) yields

$$\dot{e} + K_p e = 0. \qquad (7)$$

Then, $e \to 0$ as $t \to \infty$ when $K_p > 0$. However, as Q_i and the function $M(y)$ are not exactly known, to obtain v_r^* in (5) we use an estimate of Q_i, denoted

344

$\hat{Q}_i$ and estimate of $M(y)$, denoted $\hat{M}(y)$. The measured values of the molten steel y and roll gap x_g are used to estimate $M(y)$. Due to the estimated error $\tilde{Q}_i := Q_i - \hat{Q}_i$ a control term called supervisory control u_s, is added to v_r^* to guarantee $e \to 0$ as $t \to \infty$. The term *supervisory control* is inspired in the variable structure with sliding mode technique [6] and [7], which is of the form $u_s := A \ sgn \ (e)$ with sgn being the sign function and A an upper bound on $\left|\tilde{Q}_i\right|$. The control law thus becomes

$$v_r^* = \frac{1}{Lx_g}\left[-\hat{M}(y)K_p e + \hat{Q}_i + u_s\right]. \qquad (8)$$

From now on we drop the y in all the functions of y.

3.2. Fuzzy Controller

In order to compensate for modeling errors in the strip-caster system, an additional fuzzy control law $u_c = \tilde{M}_c K_p e$ is added to v_r^*, where $\tilde{M}_c$ is a fuzzy control term that approximates $\tilde{M} = M - \hat{M}$. The final control law may be thus described as

$$v_r^* = \frac{1}{Lx_g}\left(-\hat{M}K_p e + \hat{Q}_i - u_c + u_s\right) \qquad (9)$$

where $u_c := \tilde{M}_c K_p e$.

The *fuzzy logic system used in this paper may be formulated using the Mamdani's Method, that has been successfully applied to a variety of industrial processes and consumer products or the Takagi and Sugeno's Method that has been successfully applied to many practical problems* [7].

Mamdani's Method:
This fuzzy logic system uses the singleton fuzzifier, the center average defuzzifier, the product inference rule and a fuzzy rule base that consists of a collection of fuzzy IF-THEN rules of the following form

$$R(\ell): \quad IF \ y \ is \ F_1^\ell \ and \ \dot{e} = -\dot{y} \ is \ F_2^\ell \quad (10)$$
$$THEN \ \tilde{M}_c \ is \ G^\ell$$

where F_1^ℓ and F_2^ℓ are the input fuzzy sets, G^ℓ the output fuzzy set, $(y, \dot{e}) \in U_y$ and $\tilde{M}_c \in U_y$, with $U_y := [y_d - \delta_y, y_d + \delta_y] \subset R^n$ input and output linguistic variables, respectively, and $\ell = 1, 2, ..., r$

linguistic rules. The schematic fuzzy logic system adopted is presented in Figure 4.
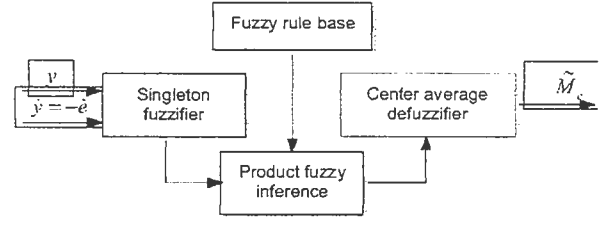

Figure 4. Schematic fuzzy logic system.

Takagi and Sugeno's Method:
Instead of considering the fuzzy IF-THEN rules as in (10), Takagi and Sugeno [8] proposed the following fuzzy IF-THEN rules

$$L^{(\ell)}: \quad IF \ y \ is \ F^\ell$$
$$THEN \ \begin{cases} \dot{y} = A_\ell y + B_\ell \ v_r \\ M_c = C_\ell y \end{cases} \qquad (11)$$

where F^ℓ is the input fuzzy set, the y and $M_c \in U_y$ with $U_y := [y_d - \delta_y, y_d + \delta_y] \subset R^n$, the state vector and output system, respectively, $v_r \in R^m$, the control input, (A_ℓ, B_ℓ, C_ℓ) are local linear models of the nonlinear plant in (4), and $\ell = 1, 2, ..., M$ linguistic rules. The configuration of Takagi and Sugeno's fuzzy system is shown in Figure 5.
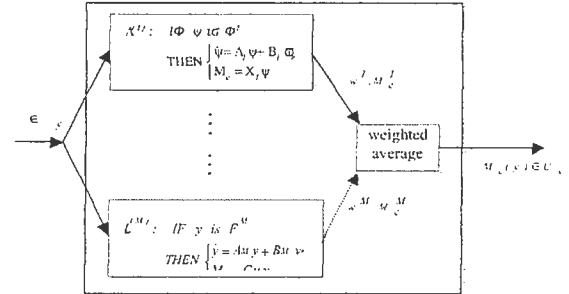

Figure 5. Basic configuration of Takagi and Sugeno fuzzy system.

This fuzzy system considered rules whose IF part is fuzzy but whose THEN part is crisp – the output is a linear combination of input system. In [9] is presented the constructing of the local linear models for fuzzy system Takagi and Sugeno.

Assuming that the Q_i term is effectively canceled by the compensation term $\hat{Q}_i$, the role of $\tilde{M}_c$ here is to estimate $\tilde{M} = M - \hat{M}$ as closely as possible. As the

345

fuzzy controller makes $\left|\tilde{M}_c - \tilde{M}\right|$ minimum in the compact set U_y, it is known from the Universal Approximation Theorem that there is an upper bound ε such that $\left|\tilde{M}_c - \tilde{M}\right| \le \varepsilon$ uniformly in the compact set U_y [3]. Let $\Delta\tilde{M} := \tilde{M} - \tilde{M}_c$. Then, clearly $\left|\Delta\tilde{M}\right| \le \varepsilon$.

Replacing (9) in (4) we have

$$\dot{e} = -\frac{\hat{M} + \tilde{M}_c}{M} K_p e - \frac{1}{M}(\tilde{Q}_i - u_s). \quad (12)$$

The stability of the closed loop system can be analyzed using a Lyapunov function candidate of the form

$$V = \frac{M}{2}e^2.$$

It can be showed that the closed loop stability can be assured for $\left|\Delta\tilde{M}\right| \le \varepsilon$. In fact,

$$\dot{V} = \frac{\dot{M}}{2}e^2 + Me\dot{e}$$

$$= \frac{\dot{M}}{2}e^2 + Me(-K_p e + \frac{1}{M}(-\tilde{Q}_i + \Delta\tilde{M}K_p e) + u_s))$$

$$= \frac{\dot{M}}{2}e^2 - MK_p e^2 - \tilde{Q}_i e + \Delta\tilde{M}K_p e^2 + u_s e$$

$$= -(M - \Delta\tilde{M} - \frac{\dot{M}}{2K_p})K_p e^2 - \tilde{Q}_i e + A|e|.$$

By choosing an appropriate value for the amplitude A since the sign of e and $\tilde{Q}_i$ is the same we can write

$$\dot{V} \le -(M - \Delta\tilde{M} - \frac{\dot{M}}{2K_p})K_p e^2.$$

Thus, the derivative of V can be made definite negative by choosing appropriately K_p since $\dot{M}$ is bounded due to the system geometry constraints.

4. Simulation Results

In this section, results of simulations are presented for a PI controller, a feedback linearization controller and a feedback linearization controller with compensation for modeling errors. In the design of the fuzzy control law u_c we used seven linguistic rules, $r=7$ in (10). The input and output membership functions adopted are as in Figure 6.
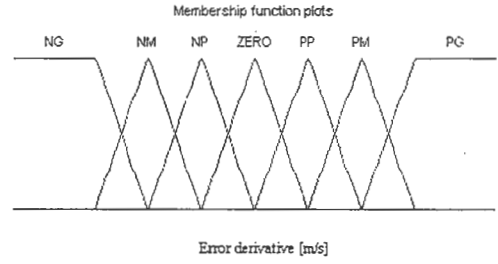

Figure 6. Fuzzy control law membership functions.

In the simulations, we assumed that the gap and the speed disturbances signals are periodic because the common roll eccentricity disturbance that occurs in the rolling process is nearly periodic. The desired values of gap, level, and speed are chosen as 0.002[m], 0.13[m], 0.5[m/s], respectively. The proportional and integral gains of the conventional PI controller are set as 150 and 0.0005, respectively.

The results developed in the previous section are applied to the IPT's pilot strip-caster plant. 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 $Q_{in} = 3.07e-3[m^3/s]$ by design of the intermediary tundish.

Figures 7 to 10 show the system responses to a step reference for the molten steel level. Inflow Q_i and roll speed disturbances as well as model errors are considered in the simulations. In Figure 7, a 30% inflow Q_i disturbance is introduced after 40s.
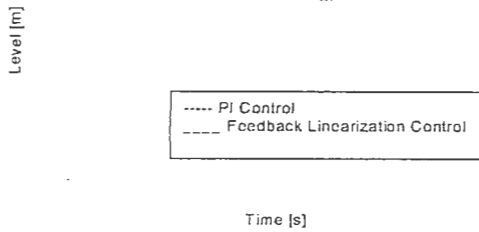
Figure 7. Molten steel level responses to a step reference and to a inflow step disturbance.

In Figures 8 and 9 results with a feedback linearization controller are presented and compared to the results with a conventional PI for a roll angular speed disturbance of 30% of its operating amplitude and containing up to the third harmonics. In addition, to reflect the roll eccentricity effects in the system modeling, in Figures 10 and 11 we present results for a gap disturbance of about 10% around the desired roll gap and containing up to the third harmonics [3]. Note that the simulation results shown in Figures 10 and 11 were obtained without considering the DC motor dynamics when the control inputs are left free to vary. Clearly, the simulation results show the superiority performance of the feedback linearization controller with a fuzzy control law.
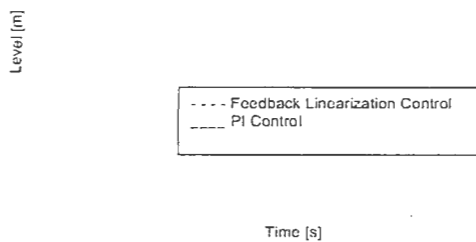

Figure 8. Molten steel level responses to a step reference with disturbance in the roll rotating speed.
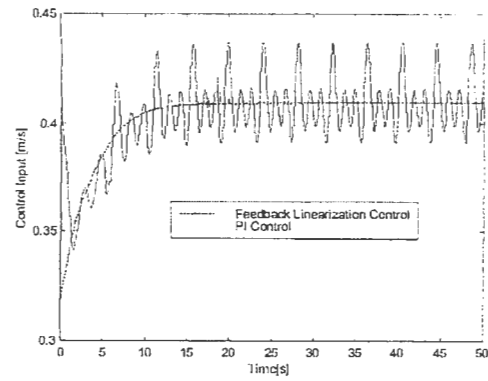

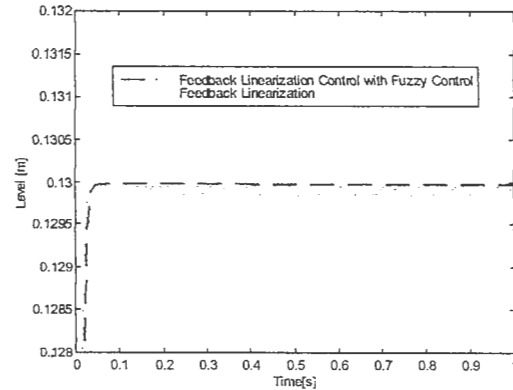Figure 9. Control input responses to a step reference with disturbance in the roll rotating speed.

Figure 10. Molten steel level responses to a step reference with disturbance in the roll gap.
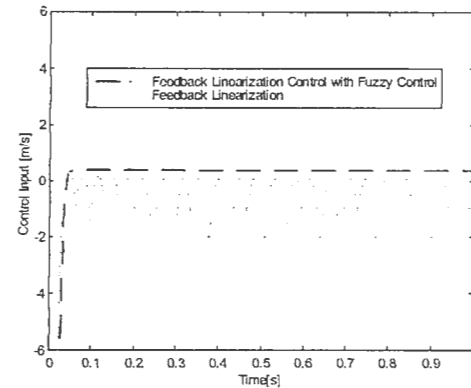

Figure 11.Control input responses to a step reference with disturbance in the roll gap.

5. Conclusion

In this work a nonlinear control strategy for the molten steel level for a strip-caster plant installed at the IPT São Paulo is proposed. A feedback linearization controller is applied in order to achieve high performance regulation. The simulation results show the efficiency of the proposed controller as

347

compared to conventional PI controllers. In order to compensate for modeling errors that inevitably occurs in the strip-caster system, an additional fuzzy control term was added to the controller. As expected, with this fuzzy control term, the delivered control input is smooth, showing the superiority performance of the feedback linearization controller with a fuzzy control law.

6. References

[1] - COOK, R., GROCOCK, P.G., THOMAS, P.M., EDMONDS, D.V., HUNT, J.D., Development of the twin-roll casting process, *Journal of Materials Processing Technology*, pp. 76-84, 1995.

[2] - SHIN, Y.K., KANG, T., REYNOLDS, T., WRIGHT, L., Development of Twin Roll Strip Caster for Sheet Steels, *Ironmaking and Steelmaking*, Vol. 22, No. 1, pp. 35-43, 1995.

[3] - LEE, D., LEE, J.S., KANG, T., Adaptive Fuzzy Control of the Molten Steel Leve in a Strip-Casting Process, *Control Engineering Practice*, Vol. 4, No. 11, pp. 1511-1520, 1996.

[4] - TAVARES, R. P., GUTHRIE, R. I. L., Analysis of Metal Delivery System for Twin-Roll Casting Using a Mathematical Model for Turbulent Fluid Flow, Heat Transfer and Solidification, *Computer Applications in Metallurgy and Materials Processing*, The Metallurgical Society of CIM, 1998.

[5] - SANTOS, J., NASCIMENTO, R. R., TOSETTI, J.P.V., GESUALDO, E., OLIVEIRA, V.A., SALES, R. M., Modelagem e Controle do Nivel de Aço de um Processo de Lingotamento Continuo Baseado em Rolos Duplos. *Associação Brasileira de Metalurgia, IV Encontro de Especialistas em Automação*, 27-28 september, 2000, Belo Horizonte, Brasil, pp.145-153.

[6] - SLOTINE, J.J. E., WIPING, L., *Applied Nonlinear Control*. Prentice Hall, 1991.

[7] - WANG, L.X., *Adaptive Fuzzy Systems and Control*. PTR Prentice Hall, 1994.

[8] - TAKAGI, T. and SUGENO, M., *Fuzzy Identification and its Applications to modeling and Control*. IEEE Trans. On Systems, Man, and Cybern., pp.116 – 132, 1985.

[9] - TEIXEIRA, M.C.M. and ZAK, H, *Stabilizing Controller Design for Uncertain Nonlinear Systems Using Fuzzy Models,* IEEE Trans. on Fuzzy Systems, Vol. 7, Nº 2, pp. 133 – 142, 1999.