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CONTROL OF THE MOLTEN STEEL LEVEL IN A STRIP-CASTING PROCESS USING T-S FUZZY MODELS

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Abstract: This paper presents a Takagi-Sugeno (T-S) fuzzy 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. Simulation results are presented considering the real system parameters and different linearization models. For comparison, results with the Mamdani's fuzzy model are also included. *Copyright © 2002 IFAC*

Keywords: Strip-casters, twin roll, fuzzy control, Takagi-Sugeno models, Mamdani models.

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). 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

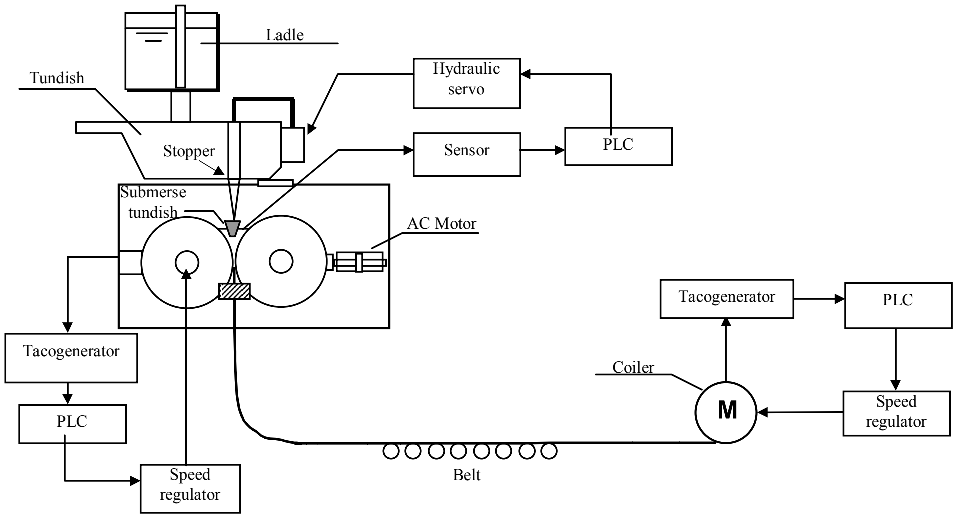

Fig. 1: Schematic layout of the strip-caster pilot plant installed at IPT São Paulo.

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 (Nascimento *et al.*, 2001). The plant is equipped with a set of Programmable Logic Control (PLC) units to perform the measurements and control.

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. Following, we describe the various components of the process.

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

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

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).

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. In terms of the level in the mill drive, (2) can be written as (Lee, *at al.,*1996).

$$\frac{dh_2}{dt} = \frac{1}{M(x_g, h_2)}\left[Q_{o1} - Q_{o2}\right] \tag{3}$$

where $M := \left[(x_g + 2R) - 2\sqrt{R^2 - h_2^2}\right]L$ and $Q_{o2} = Lx_g v_r$, with v_r the casting speed.

2.3 Hydraulic Actuator

The hydraulic servo system considered to drive the stopper valve can be described by

$$\frac{d}{v} = \frac{K_a A_p K_{eqo}}{a_1 s^3 + a_2 s^2 + a_3 s + a_4} \tag{4}$$

where $a_1 := (M_a V_t / 4\beta_e); a_2 = (M_a K_{co} + BV_t / 4\beta_e)$; $a_3 := (BK_{co} + A_p{}^2); a_4 := K_d K_a A_p K_{eqo}; b := K_a A_p K_{eqo}$

with $M_a, V_t, \beta_e, K_{co}, B, A_p, K_d, K_{eqo}, K_a$ as in Table 1. The block diagram of the hydraulic servo system is illustrated in Figure 2.

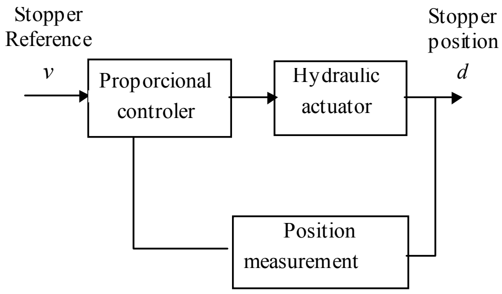

Fig. 2: Hydraulic servo actuator.

Table 1: Hydraulic parameters.

M_a	150Kg	V_t	7.9E-5m^3
β_e	7.8E8Pa	K_{co}	2E-5(m^3/s)/V
A_p	10E-4m^2	K_d	40V/m
B	1200Ns/m	K_a	30
K_{eq0}	2E-5	K_p	3.3E-12(m^3/s)/Pa

3 LOCAL LINEAR MODELS

In the space state form for $x_1 = h_1, x_2 = h_2, x_3 = d, x_4 = \dot{x}_3, x_5 = \ddot{x}_3$ we have the complete system equation using (1)-(3)

$$\dot{x} = f(x) + Bu \tag{5}$$

where $f(x) = \begin{bmatrix} \frac{1}{A_T}(c_f x_3 - k\sqrt{x_1}) \\ \frac{1}{M}(k\sqrt{x_1} - Q_{02}) \\ x_4 \\ x_5 \\ -\frac{a_2}{a_1}x_5 - \frac{a_3}{a_1}x_4 - \frac{a_4}{a_1}x_3 \end{bmatrix}; B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{b}{a_1} \end{bmatrix}$

with

$$u = v$$
$$M(x_2) = [x_g + 2R - 2\sqrt{R^2 - x_2^2}]L \cdot$$

To obtain the T-S fuzzy model we construct local linear models using the linearization formula proposed by Teixeira and Žak (1999), which has been considered because it yields a good approximate of the nonlinear system in the vicinity of the operating points even if the operating points are not equilibrium points (Cao and Frank, 2000; Guo, et al., 2000; Lam, Leung and Tam, 2001; Kim and Kim, 2001). The ith column of matrix A is as follows.

$$a_i^T = \nabla f_i + \frac{f_i(\bar{x}) - \bar{x}^T \nabla f_i(\bar{x})}{\|\bar{x}\|^2}\bar{x} \tag{6}$$

$$a_1^T = \begin{bmatrix} \frac{-K}{2\sqrt{x_1}A_T} \\ 0 \\ \frac{c_f}{A_t} \\ 0 \\ 0 \end{bmatrix} - \frac{Q_{02}}{2A_t\|\bar{x}\|}\bar{x};\ a_2^T = \begin{bmatrix} \frac{K}{2\sqrt{x_1}M} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} - \frac{Q_{02}}{2M\|\bar{x}\|}\bar{x}$$

and

$$a_3 = [0 \quad 0 \quad 0 \quad 1 \quad 0];\ a_4 = [0 \quad 0 \quad 0 \quad 0 \quad 1];$$
$$a_5 = \begin{bmatrix} 0 & 0 & \frac{-a_4}{a_1} & \frac{-a_3}{a_1} & \frac{-a_2}{a_1} \end{bmatrix}.$$

Hence, we can built the ith linear model as

$$A_i = \begin{bmatrix} a_1^T & a_2^T & a_3^T & a_4^T & a_5^T \end{bmatrix}; B_i^T = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{b}{a_1} \end{bmatrix}.$$

4 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 overflow, guaranteeing a good working condition for the process. A fuzzy control law is used as an alternative to control the steel level.

4.1 T-S Fuzzy Control

The T-S fuzzy model is described by fuzzy IF–THEN rules which represent local input-output relations of nonlinear systems. The ith rule of the T-S fuzzy model is given by

Rule i: IF $z_1(t)$ is M_{i1} and ... and $z_p(t)$ is M_{ip}
THEN $\dot{x}(t) = A_i x(t) + B_i u(t)$ (7)

where $i = 1, 2, \ldots, r$ with r the number of local linear model adopted, $x(t) \in R^n$ is the system state vector,

$u(t) \in R^m$ is the input vector, $A_i \in R^{nxn}$ and $B_i \in R^{nxm}$; $M_{ij}, j = 1,2,\ldots,p$ is the jth fuzzy set associated to rule i and $z_1(t),\ldots,z_p(t)$ are the premise variables.

Let $\mu_{ij}(z_j(t))$ be the membership grade of $z_j(t)$ in fuzzy set M_{ij} and

$$w_i(z(t)) = \prod_{j=1}^{p} \mu_{ij}(z_j(t)) \quad (9)$$

with $z(t) = \left[z_1(t)\, z_2(t) \ldots z_p(t)\right]^T$. Recalling that $\mu_{ij}(z_j(t)) \geq 0$ for $i = 1,2,\ldots,r$ we have $w_i(z(t)) \geq 0$ and $\sum_{i=1}^{r} w_i(z(t)) > 0$. To obtain a T-S fuzzy model for nonlinear systems we adopt $z(t) = x(t)$ with $x(t) \in R^n$ the state vector of the nonlinear system.

Given a pair $(x(t), u(t))$, the T-S fuzzy system is inferred as a weighted average of the local linear models which is depicted by

$$\dot{x}(t) = \frac{\sum_{i=1}^{r} w_i(z(t))(A_i x(t) + B_i u(t))}{\sum_{i=1}^{r} w_i(z(t))} = \sum_{i=1}^{r} \alpha_i(z(t))(A_i x(t) + B_i u(t)). \quad (10)$$

where

$$\alpha_i(z(t)) = \frac{w_i(z(t))}{\sum_{i=1}^{r} w_i(z(t))}, \; i = 1,2,\ldots,r. \quad (11)$$

Note that, for $i = 1,2,\ldots,r$, $\alpha_i(z(t)) \geq 0$ and $\sum_{i=1}^{r} \alpha_i(z(t) = 1$.

In the fuzzy control design we use the concept of PDC. In the PDC concept each controller is distributively designed for each ith rule of the T-S fuzzy model. Considering that in the consequent parts of the T-S fuzzy model (7) we have linear models the theory of linear control can be used in the design of the controller letting it share the same fuzzy sets with the fuzzy model as follows

$$\begin{aligned} &\text{R } (i)\text{: IF } z_1(t) \text{ is } F_1^i \text{ and} \ldots \text{and } z_p(t) \text{ is } F_p^i \\ &\qquad \text{THEN } \; u(t) = -K_i x(t). \end{aligned} \quad (12)$$

Using (9), the fuzzy controller for T-S fuzzy model (7) is also inferred as a weighted average of the controllers designed for each rule of the T-S fuzzy model that is

$$u(t) = -\sum_{i=1}^{r} \alpha_i(z(t)) K_i x(t), \quad (13)$$

for $\alpha_i(z(t))$ as in (11). Using the control law (13), the T-S fuzzy model (10) may be described as

$$\dot{x}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} \alpha_i(z(t)) \alpha_j(z(t))(A_i - B_i K_j)x(t). \quad (14)$$

A sufficient condition for the stability of the feedback T-S fuzzy system (14) can be obtained using a quadratic Lyapunov function candidate of the type $V(x(t)) = x(t)^T P x(t)$. The fuzzy control design method used consists in finding local feedback gains K_j, $j = 1,2,\ldots,r$, for the consequent parts in (12) such that the feedback T-S fuzzy system (14) is stabilizable as in Teixeira *et al*. (2000) and Tanaka *et al*. (1998).

Considering the equilibrium points:

$$\bar{x}_1 = (\frac{Q_{02}}{k})^2; \bar{x}_2; \bar{x}_3 = \frac{Q_{02}}{c_f}; \bar{x}_4 = \bar{x}_5 = 0; \bar{u} = \frac{b}{a_1}$$

we propose the following three fuzzy rules to describe the process

$$\begin{aligned} &\text{1st rule: IF } x_2(t) \text{ is about } 0.12 \\ &\qquad \text{THEN } \dot{x}(t) = A_1 x(t) + B_1 x(t) \end{aligned}$$

$$\begin{aligned} &\text{2nd rule: IF } x_2(t) \text{ is about } 0.13 \\ &\qquad \text{THEN } \dot{x}(t) = A_2 x(t) + B_2 x(t) \end{aligned}$$

$$\begin{aligned} &\text{3rd rule: IF } x_2(t) \text{ is about } 0.14 \\ &\qquad \text{THEN } \dot{x}(t) = A_3 x(t) + B_3 x(t) \end{aligned}$$

The resulting control law is of the form

$$\begin{aligned} &\text{1st rule: IF } x_2(t) \text{ is about } 0.12 \\ &\qquad \text{THEN } u(t) = -F_1 x(t) \\ &\text{2nd rule: IF } x_2(t) \text{ is about } 0.13 \\ &\qquad \text{THEN } u(t) = -F_2 x(t) \\ &\text{3rd rule: IF } x_2(t) \text{ is about } 0.14 \\ &\qquad \text{THEN } u(t) = -F_3 x(t) \end{aligned}$$

The controller vector gains F_1, F_2 and F_3 are obtained as in Teixeira *et al*. (2000) and are shown in Table 2. An schematic of the steel level control unit is shown in Figure 3 bellow.

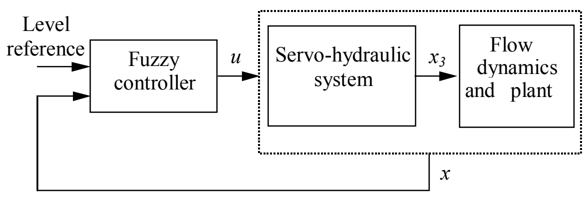

Fig. 3. Schematic of the steel level control unit using the T-S fuzzy model.

4.2 Mamdani Fuzzy Control

The fuzzy logic system used 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 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 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.

R(l): IF e is F_1^l, $\dot{e}$ is F_2^l and h_1 is F_3^l

THEN the stopper reference for d is G_4^l with confidence degree $\alpha_{1234} \in [0,1]$

where $l = 1, 2, ..., r$ are the number of linguistic rules; F_1^l, F_2^l and F_3^l are the input fuzzy sets and G_4^l the output fuzzy sets; $(e, \dot{e}) \in U_y$, $h_1 \in V_{h_1}$ and $d \in R_d$, with U_y, V_{h_1}, R_d input and output linguistic variables given by

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

In the 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 $\mu_R(w,v)$ where $w \in U_y$ 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

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

Equation (8) can be illustrated by the following statement: the strength of the relationship that links the linguistic terms F_1^l, F_2^l, F_3^l 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 the stopper reference for d is G_4^l.

The molten steel level basic control configuration with the Mamdani is shown in Figure 4.

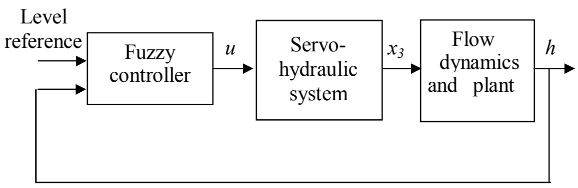

Fig. 4. Schematic of the steel level control unit using the Mamdani fuzzy model with $h := [h_1 \quad h_2]^T$.

5 SIMULATION RESULTS

All results were obtained considering the stopper actuator dynamics. The radius and width of the roll cylinders are both 0.375[m], the intermediary tundish height is $h_1 = 0.11$, the stopper valve position maximum is 0.05[m]. The molten steel levels in normal operation are in the interval $\bar{h}_2 \in [0.12 \ \ 0.14]$ 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. In the design of the Mandami fuzzy control law, we used seven linguistic rules (*r=7*) to the input fuzzy sets: error e and error derivative $\dot{e}$ and three linguistic rules (*r=3*) to the input fuzzy set of 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*). Figure 5 shows the process responses to a step reference when the desired molten steel level is chosen as 0.13m considering the different fuzzy models described in Section 3. For comparison, the responses to a PID controller with $K_p = 50, K_i = 4.5, K_d = 100$ are also given.

6 CONCLUSION

In this work fuzzy control strategies for the molten steel level in a strip-caster plant installed at the IPT São Paulo are proposed. Different fuzzy control strategies are explored in order to achieve a high performance regulation. An important feature of the fuzzy controllers are their flexibility to consider the controller design constraints in the process and control variables. The choice of the linearization procedure used in the construction of linear models in the T-S fuzzy control showed that we can reduce the conservatism of the control procedure designs based on the Lyapunov stability as we can obtain a smaller gain norms. The advantage of the Mamdani's fuzzy model is the simplicity of its control loops which follow the same structure as the PID control. 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 must include the control of the separation force and this will be considered in future work.

Table 2: T-S fuzzy gains.

T-S with Taylor linearization
F_1=[3.84E-5 8.33E-5–3.99E+1–1.67E+0 –7.81E-4]
F_2=[4.01E-5 8.72E-5 –3.99E+1–1.67E+0 –7.67E-4]
F_3=[5.64E-5 1.22E-4 –3.99E+1–1.67E+0 –7.36E-4]
T-S with Teixeira & Zak linearization
F_1=[3.39E-5 7.82E-5 –3.99E+1–1.67E+0 –7.34E-4]
F_2=[3.60E-5 8.29E-5 3.99E+1–1.67E+0– 7.17E+4]
F_3=[4.82E-5 1.10E-4 –3.99E+1–1.67E+0 6.76E-4]

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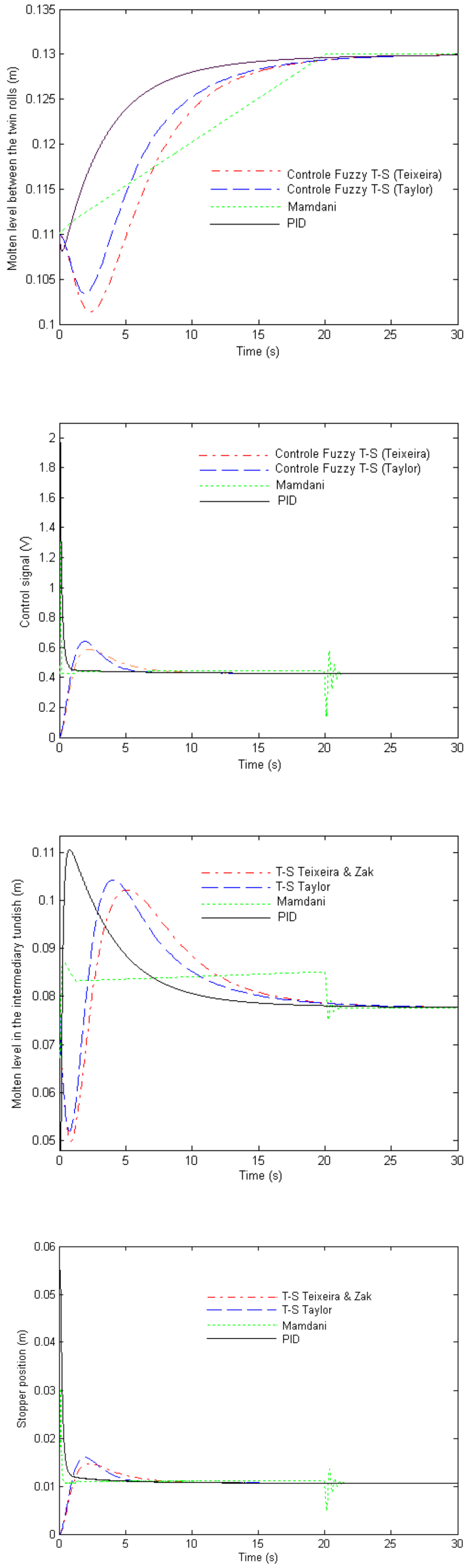

Fig. 4. Step response results.