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MODELING AND STABLE STARTUP STRATEGY FOR STRIP-CASTER

°Dukman Lee,* Jin S. Lee,* Y. H. Kim** and D. S. Lee**

* *Department of Electrical and Electronic Engineering Pohang University of Science and Technology, Pohang, 790-784, Korea*
** *Research Institute of Industrial Science and Technology, Pohang, 790-784, Korea*

Abstract. A new steel-making process, strip-casting, is introduced. The strip-casting is a new technique making the thin steel strip from the molten steel directly without resorting to repetitive reheating and hot-rolling required in a conventional steel-making method. This paper derives the mathematical model of strip caster, proposes a control strategy for stable startup operation and a fuzzy decision making rule for automatic control mode change in strip-casting process.

Keywords. Strip-casting, startup, force/gap, molten steel, roll gap, rolling force, control mode change.

1. INTRODUCTION

Recently, the research and development of strip-casting system technology is gaining much interest as a new way of casting methods for the 21st century's steel making process. The idea of strip-casting has emerged from the constant desire to produce hot-rolled thin steel strip directly from the molten steel thereby simplifying the steel making process. The method renders the separate reheating and hot-rolling processes unnecessary which require tremendous energy and operation cost [3,6]. The original idea of strip-casting can be traced back to 19th century when Sir Henry Bessemer suggested a twin roll strip-casting technology. His idea was not realized then, because many key technical components such as measurement devices and computer control technology were not sufficiently mature at that time [5]. Thanks to the phenomenal growth of steel-making and its relevant technologies however, the efforts to implement strip-casting technology revived once again these days and several countries are already actively involved in the development of full size strip-casting systems. The commercial strip-caster plant has not yet been announced but will be anytime soon. Fig.1 shows the pilot strip-caster plant that has been constructed by Pohang Iron & Steel Co. (POSCO) and DAVY International Co. based on a twin-roll system which is similar to Bessemer's [2,4,7]. The pilot plant is about 60 m in length, and is designed to produce 2 - 6 mm thick steel plates. Naturally, this complex system is equipped with many control units such as the mill drive control unit, the cooling control unit, the discharge control unit, the coiler control unit, etc. Among them, the most important control unit is the mill drive control unit (Fig. 2), which produces thin solidified steel strip from the molten steel. In this unit, the outflow of molten steel from the tundish is regulated either manually or automatically by the electrically controlled flow-control device to keep the height of the molten steel filled between the roll cylinders to a desired value. The molten steel then solidifies rapidly from the bottom, and at the same time is hot rolled by the gap positioning system. The mill drive control unit itself

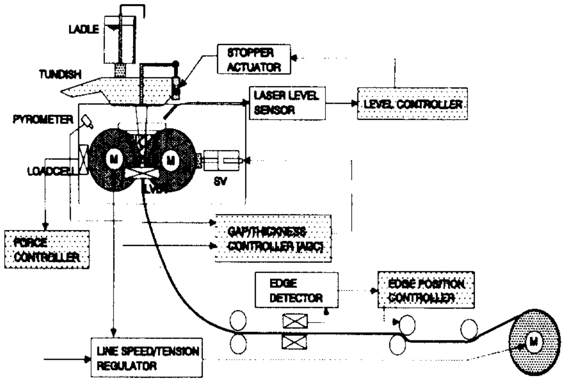

Fig. 1. Schematic layout of strip-caster pilot plant constructed in POSCO

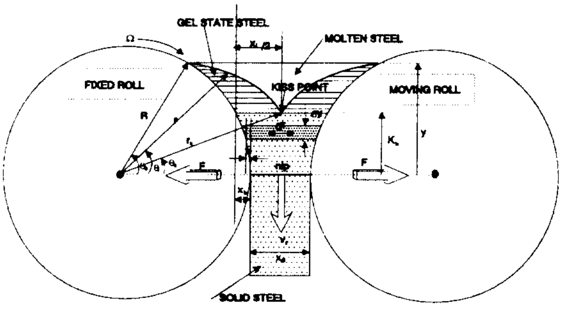

Fig. 2. Mill drive control unit

consists of three control subunits: the molten steel level control unit, the roll gap control unit, and the force/speed control unit. During the normal operation, the level control unit regulates the height of the molten steel at a fixed preset value in order to guarantee good-quality solidification. The roll gap control unit regulates the thickness of the steel strip at the desired preset value. The force/speed control unit regulates the roll force at a preset value to keep the molecular structure of the solidified steel uniform by varying the roll speed. These three control units are in fact in a coupled form, and are described as a coupled nonlinear system corrupted by various types of disturbances such as roll eccentricity, roll expansion by heating, oil film compression changes in the roll axes, roll crown bending effects, measurement delay, sensor noises, etc. It is clearly a challenging task to control the system in its coupled nonlinear form.

Actual operation of strip-caster system consists of two modes: the startup operation and the normal operation. The startup operation mode is the initial operation period when the molten steel starts to flow into the twin roll cylinders. At this period, the level control algorithm is inactive and the molten steel continues to fill in the space between the roll cylinders until motel level reaches certain level that is close to desired level. As soon as the molten steel level, the rolling force and the roll gap are reaching around the desired value, the control mode switches to normal operation and the level control algorithm becomes active. Practically, it is important to guarantee that once the control mode is in normal operation, it continues to stay in that mode all the way to the end of the casting.

By the way, unlike the normal operation period, the stable operation is highly important during startup operation period. If the gap is open excessively and/or the roll speed is increased too much, the molten steel may come out of the roll bite because the steel solidification point (kisspoint) goes far below the roll center line (nip region). This will cause all operation come to a stop. Therefore, in order to avoid the molten steel coming out from roll bite in the startup period, the kisspoint should be maintained to a desired height far above the nip region. However, since the height of kisspoint is not measurable but is proportional to the rolling force, the rolling force is controlled to a preset desired value, instead.

As a first step, in order to design a good control strategy in startup mode, a mathematical model of strip-caster is derived. Next, three heuristic startup control strategy for stable operation are proposed and are compared: first, a strategy which is about to increasing the roll gap slowly from some small to a nominal preset value in order not to come the molten steel out from the roll bite by keeping the roll gap small; second, a strategy which uses a force control routine with the adjustment of the roll gap from the start in order to keep the kisspoint above the nip region; third, a strategy which uses mixed control routines, where small gap is maintained for some time from the start and a force control routine is used for the remaining time of startup period. In order to select the most effective strategy out of the proposed ones, simulation results for each control strategy are compared. In addition to these, a fuzzy decision method is proposed to determine the time when the force control and the normal operation mode start. Thus, two simple fuzzy lookup table are designed in order to determine the proper time of them. The fuzzy rules came from the intuition and from experts.

This paper is organized as follows. Section 2 introduces the strip-caster model that is to be used mainly for simulation. Section 3 presents three control strategies for startup of strip-casting and compares them with computer simulation. Also, in order to determine the time for changing the operation mode automatically, a fuzzy decision method is presented, and Section 4 concludes the paper.

2. DERIVATION OF MATHEMATICAL MODEL FOR STRIP CASTER

In this section, a mathematical model for strip-caster is derived, where it consists of the molten steel level dynamics module, the gap dynamics module, the solidification and roll force calculation module.

2.1 *Molten Steel Level Model*

This section develops a simple mathematical model for molten steel level control unit. In the development of the mathematical model, it was assumed that the molten steel is incompressible. The continuity equation of liquid steel is then described as

$$\frac{dV}{dt} = Q_{in} - Q_{out}, \tag{1}$$

where Q_{in} is the input flow into the space between roll cylinders, Q_{out} is the output flow from the roll cylinders, and V is the volume of the molten steel stored between the twin roll cylinders. The volume V between the roll cylinders is $2SL$, where S is the shaded area as shown in Fig. 3 and L is the length of the roll cylinder.

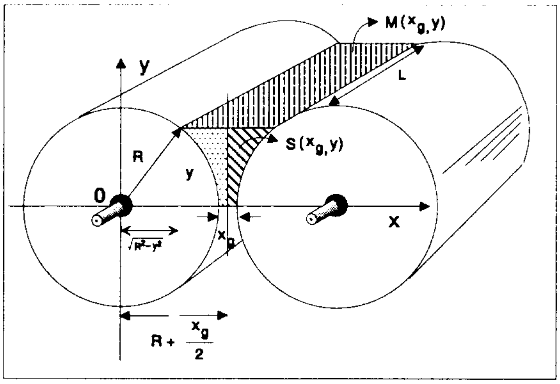

Fig. 3. Volume of molten steel filled between the twin roll cylinders.

The shaded area S is given by

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

where x_g is the roll gap and R is the radius of the roll cylinder. Then the volume V is

$$V = 2\,S\,L \tag{3}$$

and

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

If $A_r(x_g, y)$ is defined as $[(x_g + 2R) - 2\sqrt{R^2 - y^2}]$, then equation (1) becomes

$$\begin{aligned}\frac{dy}{dt} &= \frac{1}{A_r(x_g,y)\,L}(Q_{in}(h) - Q_{out}(x_g, v_r)),\\ &= \frac{1}{M(x_g,y)}(Q_{in}(h) - Q_{out}(x_g, v_r)),\end{aligned} \tag{4}$$

where $M(x_g, y) = A_r(x_g, y)\,L$ and h is the opening length of the flow-control device.

Q_{in} here is proportional to the opening length h and Q_{out} is determined by using the Bernoulli equation as:

$$Q_{out}(x_g, v_r) = L\,x_g\,v_r, \tag{5}$$

where L is the length of the roll cylinder and v_r is the roll speed [1,2].

2.2 *Roll Gap Dynamics Model*

This section develops a simple mathematical model for roll gap control unit. The roll gap dynamics module consists of two rolling roll and two hydraulic servo motor: one for moving left-side axis of the roll, the other for moving right-side axis of the roll.

As shown in Fig. 4, the hydraulic servo motor consists of a servo valve and a rectilinear actuator (cylinder and piston) that positions a load. The servo valve which is adopted in this paper is a four-port symmetric valve: one port is connected to the hydraulic fluid supply at pressure p_s, two control ports are connected to each side of the cylinder and the drain port (the two drain ports are joined) is connected to the sump. When the valve is centered, there is no motion at all. Whenever the valve is moved, high-pressure fluid enters appropriate cylinder through the control port and push the piston.

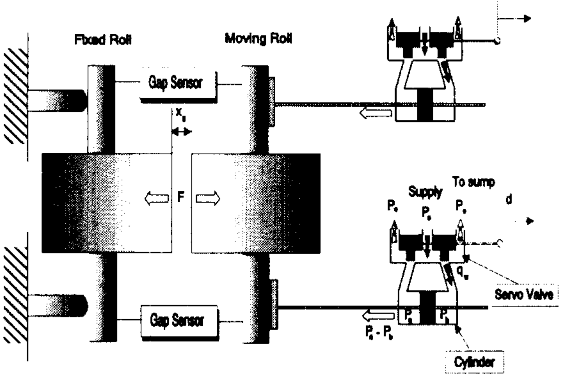

Fig. 4. Roll gap positioning system

For steady-state equilibrium, a symmetric servo valve can be modeled as

$$q = \alpha_1 d - \alpha_2 p_l, \tag{6}$$

where $q = q_w + q_l + q_c$ is the flow from the supply pump to servo valve; q_w is the flow into the cylinder from servo valve; q_l is the leakage flow; q_c is the compressed flow; α_1 and α_2 are positive constants and are valve dependent values; d is the valve movement; p_s is the supply pressure; $p_l = p_a - p_b$ is the load pressure drop and p_a and p_b are the pressure acting on each side of a cylinder.
The leakage flow q_l is given as

$$q_l = \alpha_3 p_l, \tag{7}$$

where $\alpha_3 \geq 0$.
Now, if we ignore the compressibility of the liquid, the continuity equation of flow becomes

$$q_w = q - q_l = A_{cyl}\frac{dx_g}{dt} = \alpha_1 d - (\alpha_2 + \alpha_3)p_l, \tag{8}$$

where A_{cyl} is the cross sectional area of cylinder.
Another dynamic equation relating hydraulic force p_l, external rolling force F and roll load m_r is given as

$$2 * A_{cyl} * p_l = m_r\frac{d^2x_g}{dt^2} + b_r\frac{dx_g}{dt} + k_r x_g - F \tag{9}$$

where m_r is the roll mass, b_r is the viscous friction coefficient and k_r is the elastic coefficient [1].

Finally, combining two dynamic equations of (9) and (8),

$$\frac{d^2\,x_g}{dt^2} = f_g(\frac{d\,x_g}{dt}, x_g, F) + g_g\,d, \tag{10}$$

where $f_g(\frac{d\,x_g}{dt}, x_g) = -\frac{1}{m_r}[(b_r + \frac{2\,A_{cyl}^2}{\alpha_4})\frac{x_g}{dt} + k_r x_g - F]$; $g_g = 2\,A_{cyl}\,\frac{\alpha_1}{\alpha_4 m_r}$; $\alpha_4 = \alpha_2 + \alpha_3$.

2.3 *Shell Growth Model and Rolling Force Calculation*

2.3.1. *Equation for shell solidification*

Note that the solidification process of molten steel between twin-roll cylinders. The detail diagram is shown in Fig. 2. It was assumed here that the molten steel has a uniform temperature θ_s and solidify abruptly with loss of latent heat L, and an internal heat sink has a uniform temperature θ_r. Then, the molten steel gives its heat-energy to heat-sink and as a result, the gal state molten steel turns into the solidified steel. The process of solidification is described mathematically as

$$\frac{\partial r}{\partial t} = \Omega\frac{\partial r}{\partial \theta} + \frac{b}{1 + a(r - R)} \quad \text{for } \theta_k \leq \theta \leq \theta_0,$$

where r is the radial distance from roll center to molten steel shell and speed-dependent solidification rate b is given by

$$b = \frac{\theta_s - \theta_r}{\rho_1\rho_2 L(R - r_0)\Omega}, \tag{11}$$

where ρ_1 = steel density; ρ_2 = steel resistivity; $\Omega = v_r/R$ = angular speed of roll; L = latent heat of molten steel; $a = \frac{1}{(r_0 - R)}$ [2].

2.3.2. *Calculation of Rolling Force*

Note that $r = R$ and $\theta = \theta_0$ at the molten steel surface and $r = r_k$ $\theta = \theta_k$ at the kisspoint, where $r_k = (R + x_g/2)/cos\theta_k$.

Two important variables in estimating rolling force F are the kisspoint height k_h and the steel compression $2(x_k - x)$ from kisspoint to nip region, where x_k and x are respectively derived by trigonometry as

$$x_k = R\sqrt{\left[2 - (\frac{k_h}{R})^2\right] - \left[2\sqrt{1 - (\frac{k_h}{R})^2}\right]} \quad \text{and}$$

$$x = R\sqrt{\left[2 - (\frac{y}{R})^2\right] - \left[2\sqrt{1 - (\frac{y}{R})^2}\right]}.$$

Now, if we assume that the force F is proportion to the integrated compressive strain of the solid steel between the nip and the kiss height region, then it can be formulated as

$$F(y, x_g, v_r) = \lambda\int_0^{k_h}\frac{2(x_k - x)}{x_g + 2x}dy, \tag{12}$$

where λ is the strip stiffness parameter which is dependent on roll width and steel type [2].

2.4 *Combined Strip Caster Model*

The combined dynamic equation for strip-cater shows that all sub-system are mutually coupled and has some nonlinear properties: the molten steel level is affected by the variations of roll gap and roll speed; the roll gap is affected by the variations of rolling force; the rolling force is affected by the variation of roll gap and kisspoint; the kisspoint is affected by the variation of molten steel level, roll speed and steel properties.
The block diagram of a combined strip-caster system is shown in Fig. 5. The whole equations describing the dynamics of strip-caster are rewritten here for simplicity.

$$\dot{y} = \frac{1}{M(x_g, y)}(Q_{in}(h) - Q_{out}(x_g, v_r)) \tag{13}$$

$$\ddot{x}_g = f_g(\dot{x}_g, x_g, F) + g_g\,d \tag{14}$$

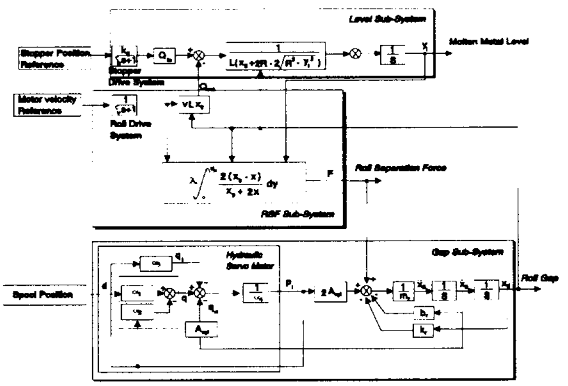

Fig. 5. Block diagram of combined strip-caster model.

$$F(y, x_g, v_r) = \lambda \int_0^{k_h} \frac{2(x_k - x)}{x_g + 2x} dy, \tag{15}$$

where $M(x_g, y) = A_r(x_g, y)\, L$ and $Q_{out}(x_g, v_r) = L\, x_g\, v_r$; $f_g(\frac{d\,x_g}{dt}, x_g) = -\frac{1}{m_r}[(b_r + \frac{2\,A_{cyl}^2}{\alpha_4})\dot{x}_g + k_r x_g - F]$; $g_g = 2\,A_{cyl}\,\frac{\alpha_1}{\alpha 4 m_r}$; $\alpha_4 = \alpha_2 + \alpha_3$; λ is the strip stiffness parameter.

The control outputs of this system are the molten steel level y, the roll gap x_g and the rolling force F whereas the control inputs of this system are the opening length h of the flow control device, the spool position d of the hydraulic servo motor and the velocity reference v_r of roll motor.

3. CASE STUDY FOR STARTUP OF STRIP CASTING

The good regulation property is absolute in the normal operation period whereas in startup operation period, the stability is more important than the good regulation. To achieve this purpose in startup operation period, a new control strategy which is different from the normal control strategy is necessary. In this section, three heuristic control strategies are considered. To easy reader's understanding, a simulation is performed for each control strategy, and their properties are discussed.

In normal operation period, the desired roll gap, the desired molten steel level and the desired rolling force are 3 mm, 215 mm and 15 ton, respectively. The startup operation period is about between 0 and 6 sec whereas the normal operation period starts about 6 sec by either manually or automatically. In the following, the force/speed controller means the force regulation controller done by varying the roll speed whereas the force/gap controller means the force regulation controller done by varying the roll gap. In the background, it was assumed that the three controllers for molten steel level regulation, roll gap regulation and force regulation are already designed properly to give reasonable performance. Note that the force/speed controller is working for all times.

Strategy 1: A linear gap increasing strategy (Fig. 6).

Since the desired roll gap at normal operation period may be rather large, there is much possibility that the molten steel come out unsolidified from the roll bite. Therefore, the desired roll gap is decreased small roll gap, 2 mm, to maintain the rolling force. However, the roll gap should be the normal roll gap, 3 mm, after startup period, it is increased linearly at slow speed. The simulation result is shown in Fig. 6.

This strategy is rather simple but can be a solution for stable operation. However, this strategy may generate a large force peak due to small roll gap, and there is no much freedom for force regulation with slow force/speed control only.

Strategy 2: A force/gap control strategy (Fig. 7).

In order to maintain proper rolling force promptly, the gap regulation controller is replaced by the force/gap controller during startup operation period, because the sensitivity of rolling force with respect to roll gap is so keen.

However, it is noted that this strategy need much attention on selection of desired rolling force during startup operation period. During time interval between 1 and 2 sec, the force will not be easily controlled by force/gap and force/speed controller partly because the molten steel falls between the twin roll cylinders and makes force peak which is uncontrollable, and partly because it takes time for force/speed controller to compensate the force error due to its zero initial velocity. Therefore, if the desired rolling force is set below the initial force peak like Fig. 7, then the roll gap increases to compensate the force error. This is very dangerous situation. Otherwise, the desired force is set to a high value, the roll gap can be too small. Thus, it may generate large force peak and some impurity between the roll may damage the rolls.

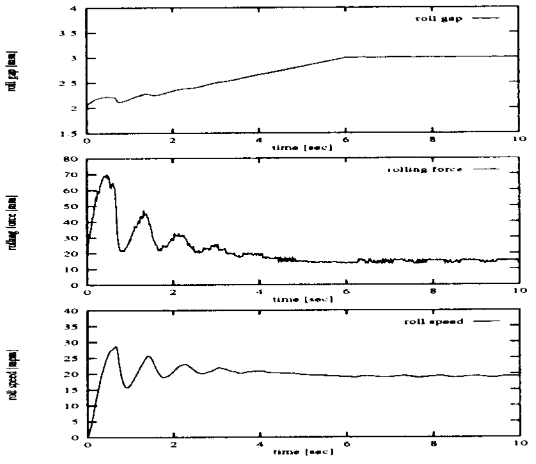

Fig. 6. Simulation of strategy 1

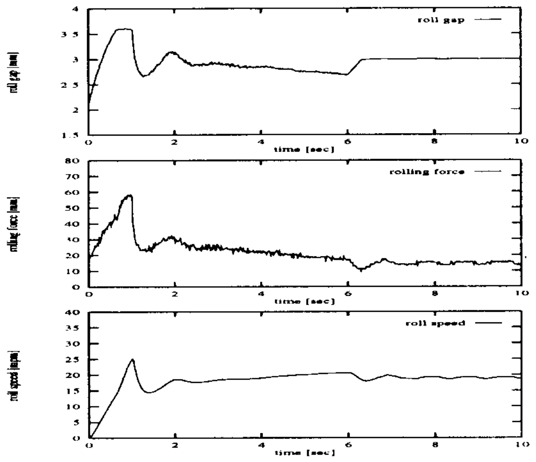

Fig. 7. Simulation of strategy 2

Strategy 3: A mixed startup strategy (Fig. 8).

In order to supplement the shortcomings of strategy 1 and strategy 2, a mixed strategy is proposed. Since the force/gap controller may cause unstability during the initial period between 1 and 2 sec in this simulation, the gap regulation is performed in that period with a fixed small gap, 2 mm. After initial period, the force/gap controller takes over and maintains the force around the desired force. And if the molten steel level and the rolling force are proper, then the control mode is changed to normal operation mode and the roll gap regulation controller takes over again with desired roll gap, 3 mm.

This strategy shows more stable operation than that of others. However, the initial roll gap should be designed properly to avoid large force value and roll damage.

In the strategy 3, it needs automatic algorithms which select the time when the force/gap controller runs and the time when the control mode is changed to normal operation mode. In order to solve this problem, a simple fuzzy decision method [8] is introduced. The block diagram is shown in Fig. 9. The force/gap

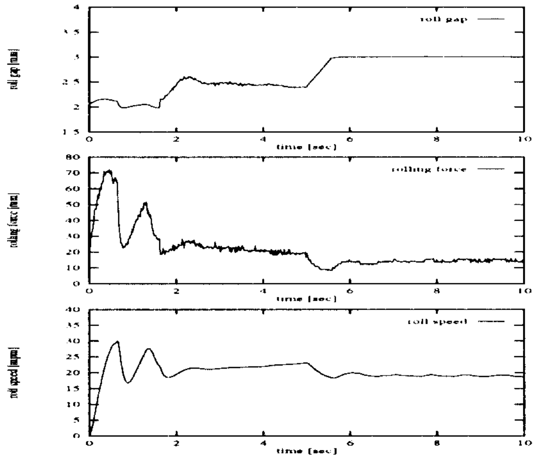

Fig. 8. Simulation of strategy 3

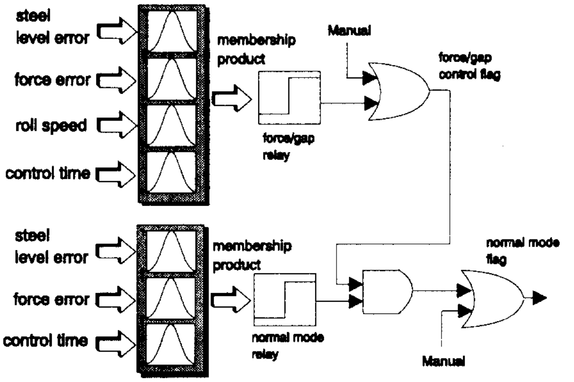

Fig. 9. Block diagram of fuzzy auto startup

control routine starts when the membership product value as shown in Fig. 9 is above a preset value, where the molten steel level error, the rolling force, the roll speed and the control time should be in the due range so that the force/gap flag is on. Similarly, the normal control mode starts when the membership product value is above a preset value and force/gap control flag is on. According to this method, the force/gap flag is on at 1.627 sec and the normal mode flag is on at 5.028 sec in Strategy 3.

4. CONCLUSION

This paper introduced a new steel making process, strip-casting, and proposed a control strategy for stable startup operation. Also, for automatic mode change, a fuzzy decision making method are introduced. The simulation tests showed that the strategy 3 among the proposed ones should be used for stable startup. It is also shown that a simple fuzzy product inference method with gaussian type membership function can give more flexibility for automatic control mode change.

As a future study, a general nonlinear control method is necessary to control the nonlinear and coupled strip-caster system, which is a challenging task.

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