Development of Mold Level Controller using Sliding Mode Control in a Continuous Casting Processing

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Abstract

A sliding mode control was applied to mold level control in the continuous casting process. The parameters of the mathematical model are obtained by simulation with the data measured in POSCO's no.2 caster and adjusted though on-line test. The new controller based on VME bus system has parallel interface with a conventional controller. The sliding gate can be controlled by the controller selected between the developed and the conventional controller. Developed controller takes account of casting speed, tundish weight, mold width and etc. The deviation magnitude of the mold level was reduced by the developed controller.

1 Introduction

Continuous casting process is to product continuous slab using molten steel delivered in large ladles from a smelting process. The slab is cut into lengths to form the raw materials for subsequent processing. Molten steel is supplied continuously from a blast furnace in large ladles for casting continuity. The molten steel in a ladle flows into a tundish through the long nozzle or the shroud nozzle as shown in figure 1. The tundish has two molds and where molten steel is poured into each mold via submerged entry nozzles. The molten steel is solidified passing a mold and water cooling zones. The resultant slab is withdrawn by pinch rolls and cut by a suitable lengths for direct sale, rolling or other production.

Uniformity in mechanical properties of the slab affects quality of subsequent rolling processes. One of the most important factors deciding quality of the slab is fluctuation of the molten steel level in the mold. That is, smoothing pouring without fluctuation in the mold level means improvement in quality of the slab and protects break-out problem and allows high speed casting process.

If molten steel surface fluctuates severely, forming oscillation marks on the slab is unstable, powder is added into the molten steel, solidification of molten steel is not uniform by change of the flow and etc. It makes quality of the slab low and defects on the slab.

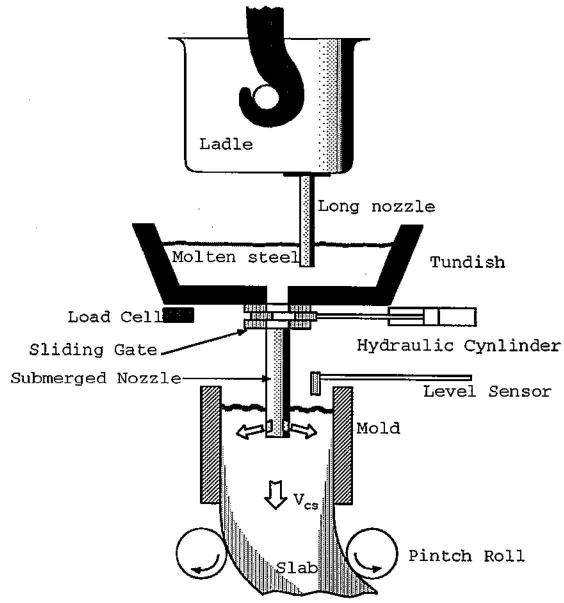

Figure 1: schematic overview of casting process

The causes of fluctuation of the molten steel level are the change of the flow coefficient in the sliding nozzle and the bulging occurred in the pinch rolls. The bulging makes serious problems in the level control. During casting, molten steel sticks to the sliding gate and the immersed nozzle. It changes the cross area of the sliding gate and the nozzle. These act on the mold level control as disturbance.

To compensate the disturbance is a important topic in the mold level control and many controllers was proposed for this. Most of mold level controllers have used the conventional PID control. But these days, new controllers have been developed using advanced control algorithm in order to compensate unexpected disturbances and stabilize the level. In this paper, a new controller developed using the sliding mode control to compensate the disturbance was proposed.

2 Modeling of mold level

The mold level control problem can be considered as one in liquid level control. To build the model of molten steel, we can take a control volume like in

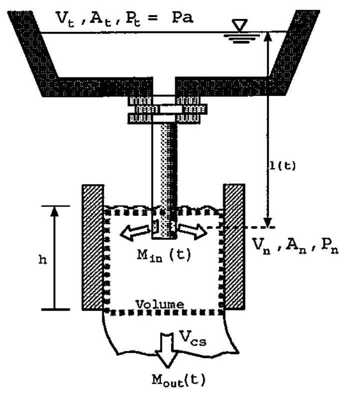

Figure 2: one dimensional flow

figure 2. If molten steel is assumed to be incompressible and to have constant specific volume, the change of control volume is the difference between inlet and outlet flow;

$$\Delta Q = A_m \frac{dh}{dt} = A_n V_n - A_m V_{cs} \tag{1}$$

where h is the height of molten steel surface, A_n is outlet area and V_n outlet flow rate in a nozzle and A_m is surface area of a mold and V_{cs} casting speed.

In order to keep the mold level stable in a casting process, the amount of molten steel enters the mold should be equal to that of withdrawn slab. In equation (1) A_m, h, A_n and V_{cs} are measurable and V_n is unmeasurable but is to be inferred. The outlet flow rate, V_n, is the manipulated control variable. Since the outlet flow rate is controlled by moving a sliding gate, we can take $A_s V_s$ as the control variable instead of $A_n V_n$. But V_s is unmeasurable. With the investigation of the data of steady state casting process, A_s is assumed to be A_n. So we can use the outlet flow rate as V_n instead of V_s. Finally, the control volume equation is

$$\frac{dh}{dt} = \frac{1}{A_m}\left(A_s V_n - A_m V_{cs}\right) \tag{2}$$

To calculate the exit speed of the molten steel from the submerged entry nozzle, the flow along a streamline from the tundish to the mold is simplified and Bernoulli's equation is applied as shown in figure 2.

$$\frac{P_t}{\rho} + \frac{1}{2}V_t^2 + gl = \frac{P_n}{\rho} + \frac{1}{2}V_n^2 \tag{3}$$

Since $P_t \approx P_n \approx P_a$(atmospheric pressure), the pressure terms cancel. Outlet area of the nozzle is very small than surface area of the tundish, so that the ratio A_n^2/A_t^2 is negligible, and we get the speed of molten steel at the immersed nozzle as follows;

$$V_n = \sqrt{2gl} \tag{4}$$

The sliding gate consists of a moving gate and a fixed gate. Molten steel flows through the cross area made by two gates. The sliding gate has a dead zone, $40mm$, as shown in figure 3. The cross area, A_s, made by moving and fixed parts is expressed as following;

$$\begin{aligned} A_s &= 1600\pi + 3200 \arcsin\left(\frac{x_s - 120}{80}\right) \\ &+ \frac{x_s - 120}{2}\sqrt{6400 - (x_s - 120)^2} \end{aligned} \tag{5}$$

From the equation (5), the stroke(x_s) of the sliding gate can't be extracted in a analytic form. The measured data says that the range of the position of sliding gate in steady state is $60 \sim 80mm$. In this range the cross area, A_s, can be approximated as

$$A_s = 0.447x_s^2 - 887.08 \tag{6}$$

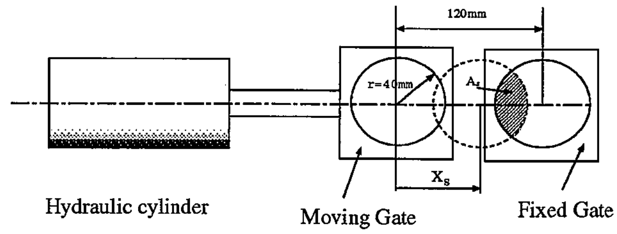

Figure 3: sliding gate

Finally, the dynamic model of the molten steel in the mold becomes

$$\dot{h}(t) = \frac{1}{A_m}\left\{(0.447x_s^2 - 887.08)\sqrt{2gl} - A_m V_{cs}\right\} \tag{7}$$

3 Sliding mode controller design

The aim of mold level controller is to maintain h as close as possible to the desired level, h_d. So, sliding surface can be defined as

$$S(t) = C_1(h - h_d) + C_2 \int (h - h_d)dt \tag{8}$$

where h and h_d are the actual level and the desired level of molten steel, respectively. The surface defined by $S(t) = 0$ can be guaranteed to be stable and attractive(i.e., system trajectories are attracted to and then stay on or near the surface $S(t)$ in state space) if the condition,

$$S(t)\dot{S}(t) \leq 0 \tag{9}$$

This requires that the specified surface is such that S^2 may be considered to be a *Lyapunov* function v, i.e., $v = S^2$, where v is positive definite and $\frac{dv}{dt} = 2S\dot{S}$ is negative definite or semi-definite. If the control law is formulated to satisfy the equation (9), the magnitude of $S(t)$ will decrease and go zero as $t \to \infty$. Equation (9) is satisfied if we define the "sliding condition" as

$$\dot{S}(t) \le -\eta_2 S - \eta_3 sat(\frac{S}{\Phi}) \tag{10}$$

where η_2 and η_3 are positive, Φ is boundary layer thickness and sat is the saturation function :

$$sat(x) = \begin{cases} x & if\ |x| \le 1 \\ sgn(x) & otherwise \end{cases} \tag{11}$$

From the equation (7), (8), (10), the desired cross area of the sliding gate is expressed as follows

$$A_s = \frac{A_m}{\sqrt{2gl}}\Bigg(V_{cs} - \eta_1(h - h_d) - \eta_2 S - \eta_3 sat(\frac{S}{\Phi})\Bigg) \tag{12}$$

With two equations, (6) and (12), the position of sliding gate can be decided.

4 Experiment

The designed controller was realized in No.2 caster POSCO. The new controller has parallel interface with a conventional controller. The sliding gate can be controlled by the controller selected between the developed and the conventional controller. Figure 4 shows the block diagram of the mold level control. The specification of the new system is

- Real time O/S : OS-9
- Bus : VME Bus
- CPU : MC68040 33MHz
- Cycle time : 100msec

The casting process is extremely dangerous. So, experiment of the new controller was undertaken carefully. At first parameters are decided by simulation using the data collected in the plant. With the parameters the first test was applied in the end of each schedule of casting process. First test result is shown in figure 5. The new controller is selected at 100sec. For this case fluctuation is large and there is lasting offset.

For second case shown in figure 6, the average of the actual level is the same as desired level, but switching phenomenon exists. In this case, the fluctuation is reduced by changing the boundary thickness layer. Third case says the new controller can manipulate the level within $\pm 2mm$ as shown in figure 7.

Many experiments can not be taken because of the schedule of the casting process. But we can compare the two controllers with experimental data in figure 8. The new controller controlled the mold level with 93% within $\pm 1mm$.

5 Conclusion

A mold level controller using sliding mode control was designed and experimented in POSCO's No.2 caster, which operated in parallel with the conventional PID controller.

The fluctuation of the mold level was decreased within some experiments. In this work, the gains are to be optimized and during the test some states such as the casting speed was not changed. But with the model designed in previous chapter, we can achieve improved mold level control disturbance rejection.

The developed controller will be applied to other continuous casting plant and billet plant.

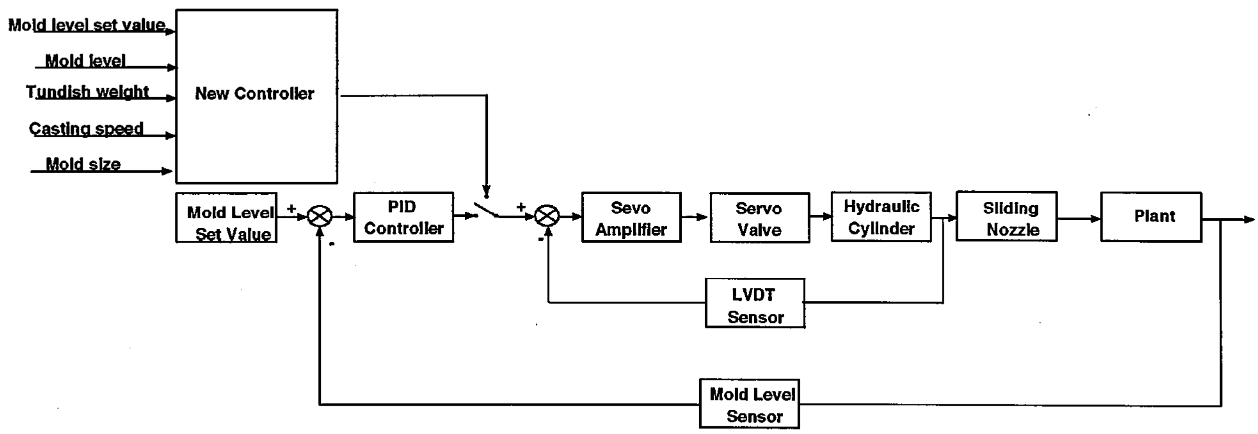

Figure 4: control diagram and interface with existing controller

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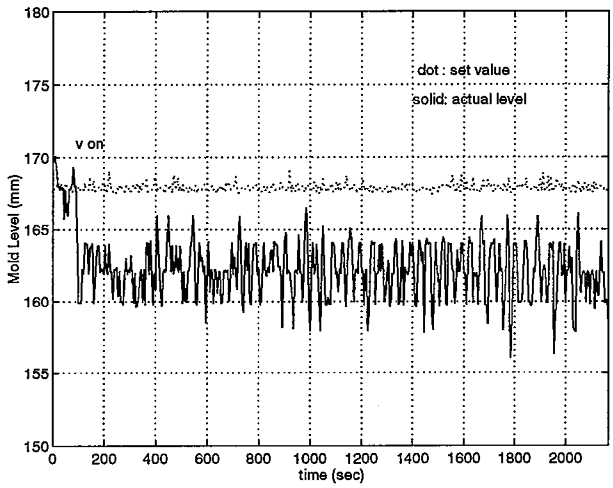

Figure 5: sliding mode control result

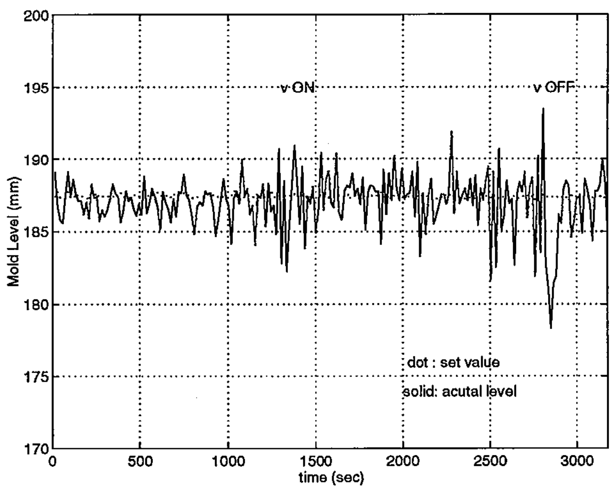

Figure 6: sliding mode control result

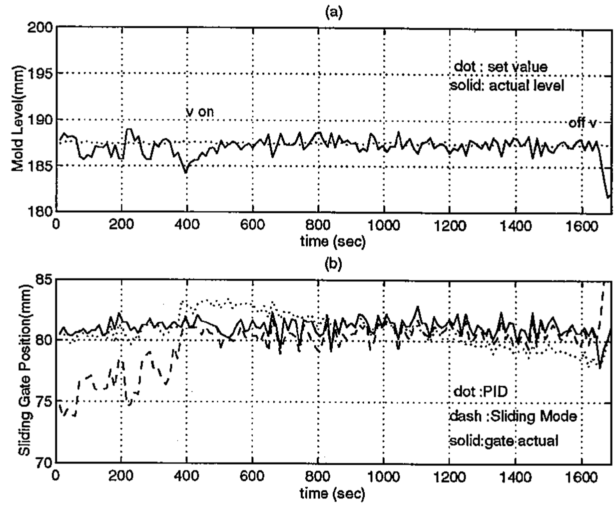

Figure 7: sliding mode control result

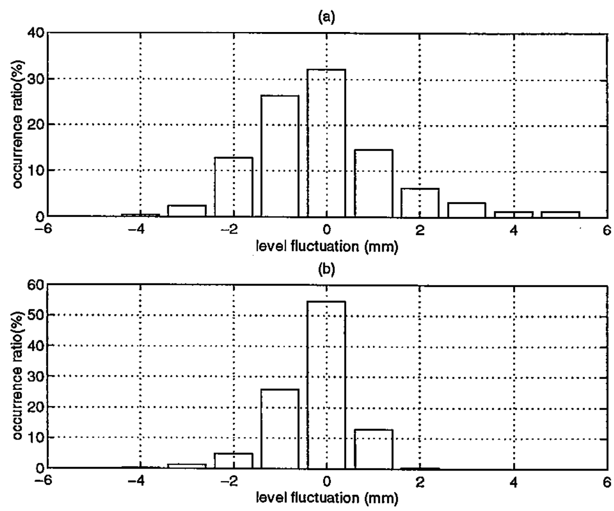

Figure 8: comparison between (a) existing controller and (b) sliding mode controller