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Improved Mold Level Control for Continuous Steel Casting by Fuzzy Logic Control

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Abstract : This paper gives a simulation study of a new fuzzy logic control(FLC) approach for the mold level control in continuous casting processes. The proposed FLC is PID type hybridizing the conventional fuzzy PI control and Fuzzy PD control with a simplified design scheme. It is shown that, compared with the conventional control, this new control strategy can achieve superior performance for steady-state response and is more robust against process parameter variations and disturbances.

Keywords : steel industry, fuzzy control, PID control, disturbance robustness.

I. Introduction

In the steelmaking process, continuous casting is used to produce slabs from molten steel for subsequent processing. The molten steel is primarily solidified in the mold. In order to improve the surface quality of the final cast slabs and assure the safety in the production of the slab caster, the fluctuation of the molten steel level in the mold should be reduced as much as possible [2]. However, the accurate mold level control is very difficult because the controlled system is nonlinear, time varying and various unexpected disturbances.

In order to solve the problem by more advanced feedback control with better disturbance rejection characteristics than conventional single-loop proportional-integral-derivative (PID) control, various methods have been developed for mold level control, such as predictive control [3], linear [3] or nonlinear cascade control [5], repetitive learning for periodic disturbance[10], and disturbance observer [1].

Fuzzy logic control (FLC) has become an active and effective approach for mold level control. Usually it is implemented at the supervisory level for adjusting the low level conventional controller [11] or implemented in parallel with the conventional controller for dealing with large disturbances [4][6]. Attempt is also done to design FLC for mold level control as a complete substitute for the conventional control. However, a better solution which achieves good steady-state performance as well as good robustness against disturbances is not found yet [6].

This paper will answer the question why FLC fail in the above attempt, and present a new FLC approach to solve the problem. A PID type fuzzy control structure by hybridizing the conventional PI-type and PD-type fuzzy controllers with a simplified design scheme will be introduced.

In this paper, the continuous casting process and mold level control are first introduced followed by a brief introduction of FLC, then the new FLC scheme is presented and its design method is described in detail, finally performance comparisons between the proposed controller and the conventional controller are given.

II. Process description

1. The continuous casting process

Fig. 1 depicts a schematic diagram of the continuous casting process based on a continuous caster of Pohang Iron & Steel Co. Ltd. (POSCO). Molten steel is transferred from the ladle into the tundish, and flows into the water-cooled mold through the sliding gate and the submerged entry nozzle(SEN). Then, the surface solidified strand is continuous drawn by the pinch roll at a determined casting speed followed by a secondary cooling stage and cut into slabs.

The mold level is measured by means of radiation detectors or eddy current sensor [2], its compensation is realized by the hydraulically activated sliding gate. Mold level fluctuation should be reduced because this will result in deterioration of the quality of cast slabs. The mold level control is very difficult, mainly because of

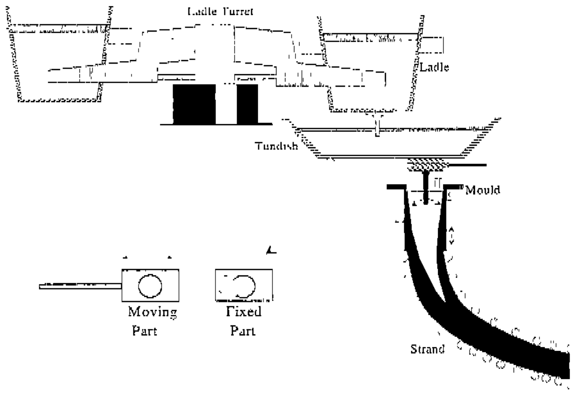

Fig. 1. A schematic diagram of the continuous casting process.

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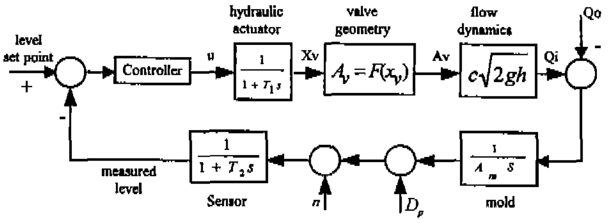


Fig. 2. Process model for mold level control.

- Non-smooth nonlinearities such as slip-stick friction, and hysterisis of the hydraulic actuator,
- Smooth nonlinearities of the valve-geometry of the sliding gate and the flow dynamics,
- Time variations caused by clogging/erosion phenomena, which are the results of settling of deposits on the sliding gate valve or submerged entry nozzle, and their wearing,
- Sudden disturbances such as unclogging caused by breakaway of the deposits after clogging.

2. The process model for mold level control

The block diagram of the process model is shown in Fig. 2.

The hydraulic actuator is approximately modeled by first-order transfer functions between the control signal u from the controller and the sliding gate position x_v with the time constant T_1.

The sliding gate valve consists of three identical plates of radius r with the outer two fixed and the center one sliding in between, the effective flow area for the molten steel is determined by the overlapping orifice area. As shown in Fig. 3, when the center plate is at position x_v (in this paper, we call it the sliding gate position), the effective flow area is given by the nonlinear function

$$A_v = F(x_v) = 2\alpha r^2 - r(3r - x_v)\sin\alpha, \qquad (1)$$

$$\alpha = \arccos\left(\frac{3}{2} - \frac{x_v}{2r}\right), \quad 2r \le x_v \le 4r \qquad (2)$$

The expression $2r \le x_v \le 4r$ represents the operational region of x_v.

The flow dynamics is described as

$$Q_i = A_v c\sqrt{2gh}, \qquad (3)$$

where Q_i is the inflow of the molten steel to the mold, g is the acceleration of gravity, h is the falling height of the molten steel from the tundish to the mold, c is the coefficient of discharge dependent on the viscosity of the steel grade and the coefficient of contraction of the sliding gate valve.

Q_0 stands for the outflow of steel from the mold and is simply computed from the casting speed v_{cs}

$$Q_0 = A_m v_{cs}, \qquad (4)$$

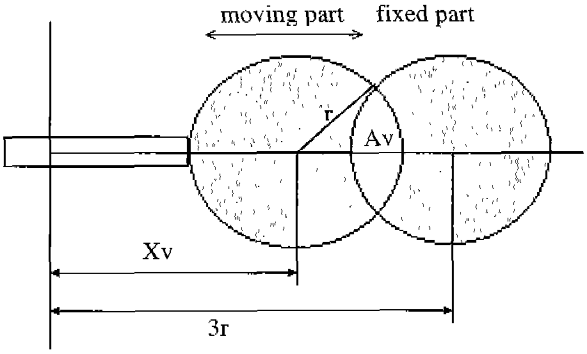


Fig. 3. Effective flow area of the sliding gate.

where A_m is the cross sectional area of the mold. The mold is a pure integrator and is described as

$$\frac{dy}{dt} = \frac{Q_i - Q_0}{A_m} \qquad (5)$$

where y is the mold level.

The typical steady-state response of the existing control system during the normal operating condition usually shows a nearly periodic oscillating nature around the setpoint, with a frequency in the range 0.05-0.1Hz and an amplitude varying between 5-15mm. It is not yet known exactly where this phenomenon comes from. Possible reasons include surface wave, bulging of the strand and the non-smooth nonlinearities of the hydraulic actuator [3][5]. In order to simulate these phenomena, a periodic disturbance term(D_p) with a given amplitude and frequency is added to the mold level y. The level sensor is also modeled by a first-order transfer function with the time constant T_2. A measurement noise n(white noise) is also added to the measurement process.

III. Controller design by fuzzy logic control

Inspired by the great success of FLC in the theoretical research and industrial applications [7][9][12], a new FLC structure for mold level control is introduced in this chapter.

1. PI, PD and PID type fuzzy controllers

FLC is usually used as proportional-integral type (fuzzy PI) or proportional-derivative type (fuzzy PD), which uses error(the difference between the setpoint and system output) and error derivative as inputs and respectively incremental control signal or control signal directly as output.

As reported in [8], PI type fuzzy controller has good performance at steady state, but gives poor performance in transient response with long rise time and a long settling time due to the internal integration operation. On the other hand, PD type fuzzy controller has good performance at the transient state, but will cause the steady-state error or the steady-state oscillation. This explains why the conventional FLCs

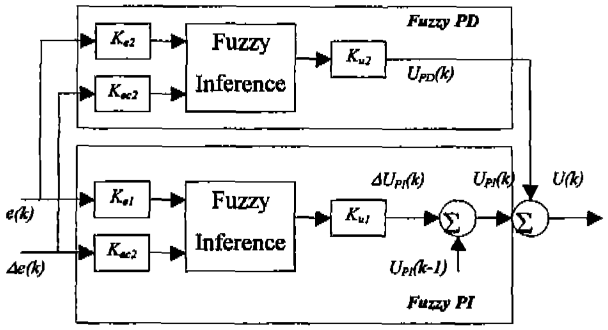


Fig. 4. Hybrid PI/PD type fuzzy control.

(PI/PD type) failed in the attempt for control of the mold level control directly. PID type fuzzy controller is also used usually by generating incremental control output from error, error derivative and acceleration error.

2. Hybrid PI/PD type fuzzy control

Theoretically, PID type fuzzy controller can enhance the performance a lot, however, the number of inputs will expand rule base greatly and makes the design task more difficult. For example, suppose that the number of fuzzy sets of error, error derivative and acceleration error are all 7, the rule base is three dimensional and the number of rules is 343 in this case. Also, further extension of the input set of the PID type fuzzy controller is theoretically possible. However, it leads to an increasing complexity of the internal structure of PID type fuzzy controller. The ability of an expert to formulate a clear and reasonable control strategy becomes a rather unrealistic assumption since the PID type fuzzy controller becomes a state variable-like controller.

In order to reduce the design complexity of PID type fuzzy controller and combine the advantages of PI/PD type fuzzy controllers, the control structure shown in Fig. 4 by hybridizing the PI/PD type fuzzy control will be introduced. The control scheme is structured with a parallel structure where the discrete form of FLC is adopted and the inputs and the outputs are normalized by scaling factors. Here only error and error derivative are used as common inputs for PI/PD type fuzzy controllers. It is a special form of PID type fuzzy control, but requires only 2 two-dimensional rule bases for the PI and PD type fuzzy controllers, respectively. Also the control structure provides a flexibility for control design, for example, the PI and PD type fuzzy controllers can have different linguistic values for the same I/O variables, different scaling factors and rule bases.

3. Controller structure for mold level control

In this paper, a simplified hybrid fuzzy control will be used for the mold level control by using the same input variables for error and error derivative (corresponding to $ke_1 = ke_2$, $kec_1 = kec_2$ in Fig. 4 and same membership function for each fuzzy linguistic values) and common data bases for the PI/PD type fuzzy controllers. This leads to the control structure as shown in Fig. 5. Because it uses only a two-dimensional rule base, it is simple in structure and easy for implementation. The scaling factors Ku_1 and Ku_2 stand for the contributions of the integration and derivative operations. The conventional PI and PD type fuzzy controllers are special cases of this control structure corresponding to $Ku_2 = 0$ and $Ku_1 = 0$, respectively.

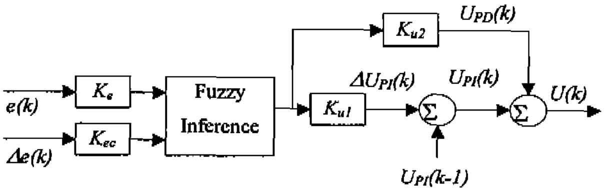


Fig. 5. Simplified PID type fuzzy control structure used for mold level control.

The realization of the fuzzy inference process is based on the standard fuzzy method consisting of fuzzification, rule base, and defuzzification [7]. The result of the fuzzy inference is weighted by two scaling factors Ku_1 and Ku_2 to get the incremental control $\triangle U_{PI}(k)$ for the PI type fuzzy controller and control $U_{PI}(k)$ for PD type fuzzy controller. The summation of $U_{PI}(k)$ and $U_{PD}(k)$ is used as the final control signal for the mold level control.

4. Design of the fuzzy controller

As shown in Fig. 6(a) and (b), for each normalized input and output variables, there are seven fuzzy sets, negative large(NL), negative medium(NM), negative small(NS), zero(ZE), positive small(PS), positive medium (PM), and positive large(PL). Triangular shaped membership functions are used for fuzzy sets of each input and singleton-shaped membership functions are used for those of the output, and their universes of discourse are all normalized in the interval [-1, 1]. For the input variable of error, a positive fuzzy set describes that the mold level is below the mold level setpoint, whilst a negative fuzzy set describes that the mold level is upper the mold level setpoint, and so on. For error derivative, a positive fuzzy set describes a decreasing mold level, whilst a positive fuzzy set describes an increasing mold level, and the fuzzy set zero(ZE) indicates a constant mold level. The fuzzy sets of the output are assigned in a similar way, a positive fuzzy set describes an increasing of the sliding gate position, whilst a negative fuzzy set describes an decreasing of the sliding gate position, the fuzzy set zero(ZE) indicates no change of the sliding gate position.

In this paper, the standard membership functions are used as shown in Fig. 6. The design of the proposed fuzzy controller includes determination of the rule base

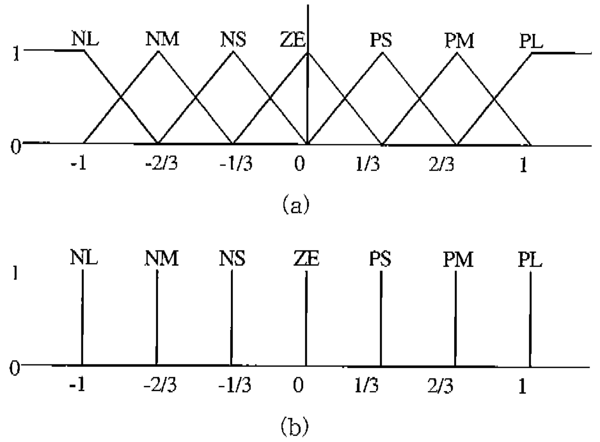


Fig. 6. Fuzzy sets for FLC I/O variables. (a) Normalized error and error derivative, (b) Singleton output.

Table 2. Fuzzy rule base.

E \ SE	NL	NM	NS	ZE	PS	PM	PL
PL	PL	PL	PL	PL	PL	PL	PL
PM	ZE	PS	PM	PL	PL	PL	PL
PS	NS	ZE	PS	PM	PL	PL	PL
ZE	NL	NM	NS	ZE	PS	PM	PL
NS	NL	NL	NL	NM	NS	ZE	PS
NM	NL	NL	NL	NL	NM	NS	ZE
NL	NL	NL	NL	NL	NL	NL	NL

and tuning of the scaling factors. Because the proposed fuzzy controller incorporates the conventional PI and PD type fuzzy controllers, an optimal PID type fuzzy controller is not an easy task. In this paper, a rule base shown in Table 2 designed for the PI type fuzzy control is chosen as the common rule base. It is designed by phase-plane as indicated in Fig. 7 and the system output trajectory plane is shown in Fig. 8 where the arrows stands for the possible tangent directions of the output trajectory.

The basic design principle for rule base is to drive the controlled system with fast response and small overshoot and undershoot. The detailed design meta-rules are listed as follows:

1) if the e and Δe are zero, then maintain the present control setting;

2) If the mold level is far away from the setpoint, a larger control signal that pulls the level toward the setpoint is applied no matter what Δe is;

3) if the error will go to zero at a satisfactory rate, then maintain the present control setting;

4) if the error is not self-correcting, then output is not zero decided by the sign and magnitude of e and Δe in order to avoid large overshoot;

5) if the error is self-correcting but too slow (Δe is small), then the output is not zero decided by the sign and magnitude of e and Δe for speeding up the response;

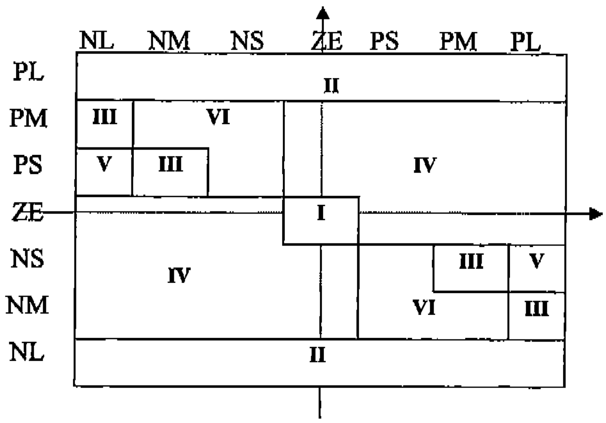


Fig. 7. Phase-plane for design of fuzzy rules (Areas of metarules).

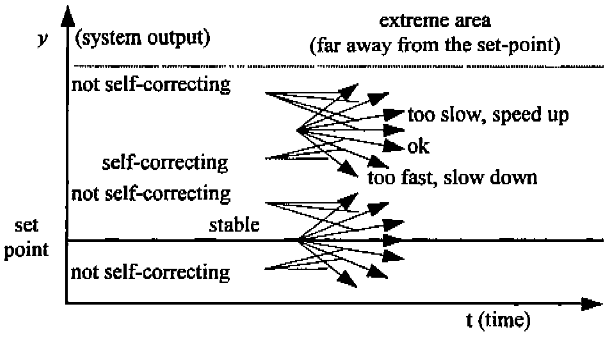


Fig. 8. Rule base design strategy.

6) if the error is self-correcting but too fast(Δe is too large), then the output is not zero decided by the sign and magnitude of e and Δe for slowing down the response to avoid large overshoot.

Tuning of the scaling factors are based on the following principles or observations, similar results were found in paper [8]:

For PI type fuzzy controller as an example(corresponding to setting $Ku_2 = 0$):

1. Scaling factor Ke: it is fixed at $1/e_{max}$, where e_{max} is the maximum absolute value of the error, this leads to the normalized error can spread all over the normalized universe of discourse [-1, +1].

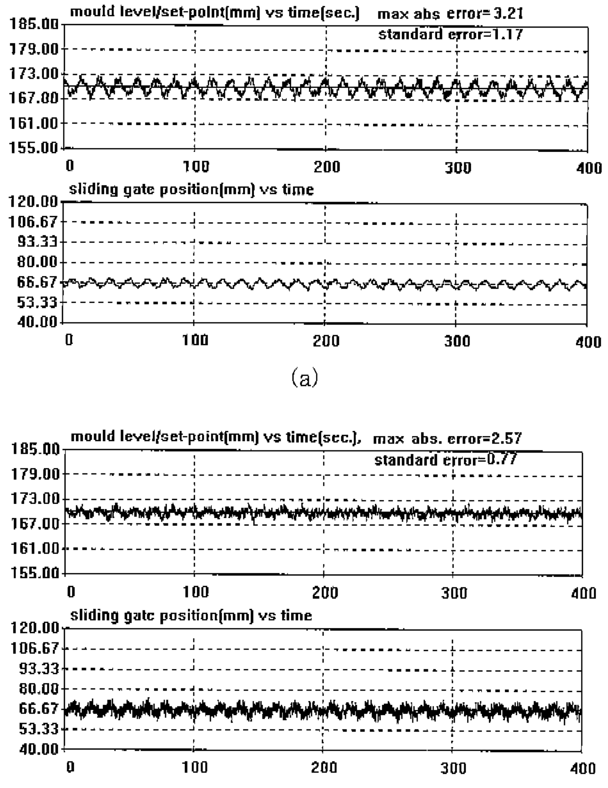
2. Scaling factor Kec: Kec/Ke has the similar influence as integral time in the nonfuzzy PI control. So decreasing Kec will speed up the response and reduce the steady state error. However, too small Kec will cause large overshoot and be more oscillatory.

3. $Kec*Ku_1$ has the similar influence as the proportional gain in the nonfuzzy PI control. If Kec keeps unchanged, increasing Ku_1 will speed up the response and reduce the steady-state error. However, too large Ku_1 will cause oscillations or instability.

For the proposed PID type fuzzy controller:

1. Scaling factor Ke is fixed at $1/e_{max}$, where e_{max} is the maximum absolute value of the error.

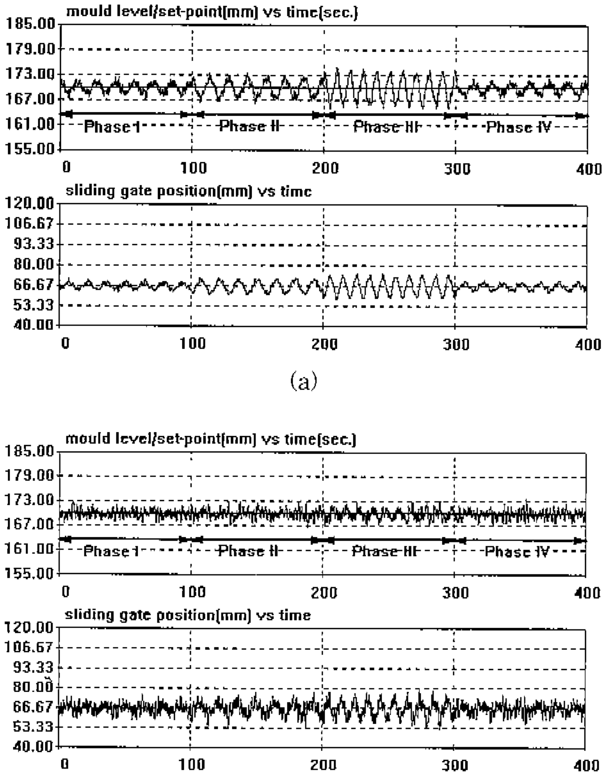
2. If Ku_1 and Ku_2 keep unchanged, increasing



(a)

(b)

Fig. 9. Steady-state response of PI & fuzzy control under periodic disturbance. (a) PI control, (b) Fuzzy control.



(a)

(b)

Fig. 10. Robust of PI and fuzzy controllers against different periodic disturbances. (a) PI control, (b) Fuzzy control.

Kec/Ke has the similar influence as increasing derivative time, as well as increasing the integral time in the PID control. This means that *Kec* has contradictory influence on transient response(fast response) and steady state response.

3. $Kec*Ku_1+Ke*Ku_2$ has the similar influence as increasing the proportional gain in the nonfuzzy PID control. If Ke and Kec are unchanged, increasing $Kec*Ku_1+ Ke*Ku_2$ will speed up the response.

4. If $Kec*Ku_1+Ke*Ku_2$ is unchanged, increasing Ku_2/Ku_1 will increase the derivative time, as well as increase the integral time.

Based on the above points, the tuning of the PID type fuzzy controller for the mold level control is used the following heuristic steps:

1. Tuning the PI type fuzzy controller first by tuning the scaling factors *Kec* and Ku_1 to get a reasonable performance.

2. Keeping the input scaling factors *Ke* and *Kec* unchanged and adding the PD type fuzzy factor Ku_2, tuning $Kec*Ku_1+Ke*Ku_2$ to get the steady state performance, and tuning Ku_2/Ku_1 to increase the transient response.

3. Normally after step 2, fairly good performance can be obtained. If not satisfactory, returning by adjusting *Kec* first and then adjusting Ku_1 and Ku_2 according to step 2, the performance can be improved further.

IV. Results

Comparison is given between the proposed control strategy and the conventional control for steady-state response and robust against disturbance and parameter variation.

1. Steady-state response under periodic disturbance

To simulate the system steady-state response, a periodic disturbance with amplitude (4.3mm) and frequency (0.07Hz) is added in the system. As shown in Fig. 9(a) and (b), clearly small fluctuation is observed. The standard error deviation and maximum absolute error is reduced from 1.17mm and 3.21mm to 0.77mm and 2.57mm, respectively. This indicates that FLC can get good steady-state performance than PI control.

2. Robust to periodic disturbances

The amplitude and the frequency of the periodic disturbance are changed during the simulation horizon. In phase I, the periodic disturbance is with amplitude 4.3mm and frequency 0.07Hz. In phase II, the amplitude is changed to 9mm with the same frequency. In phase III, the amplitude is kept at 9mm and the frequency is changed to 0.1Hz. In the last

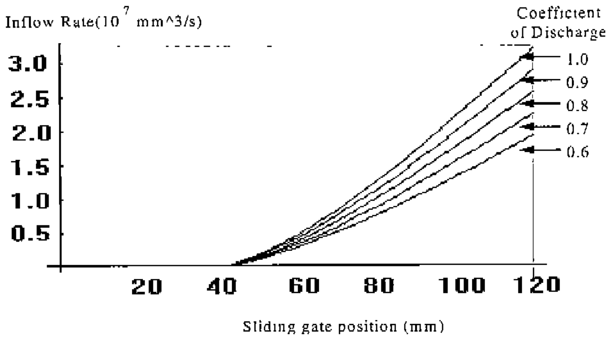


Fig. 11. Relation between Q_i and X_v with the change of the coefficient of discharge.

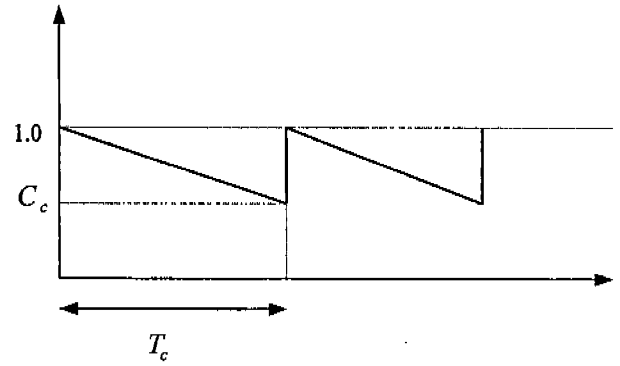


Fig. 12. Time-varying of coefficient of discharge in clogging/unclogging cycle.

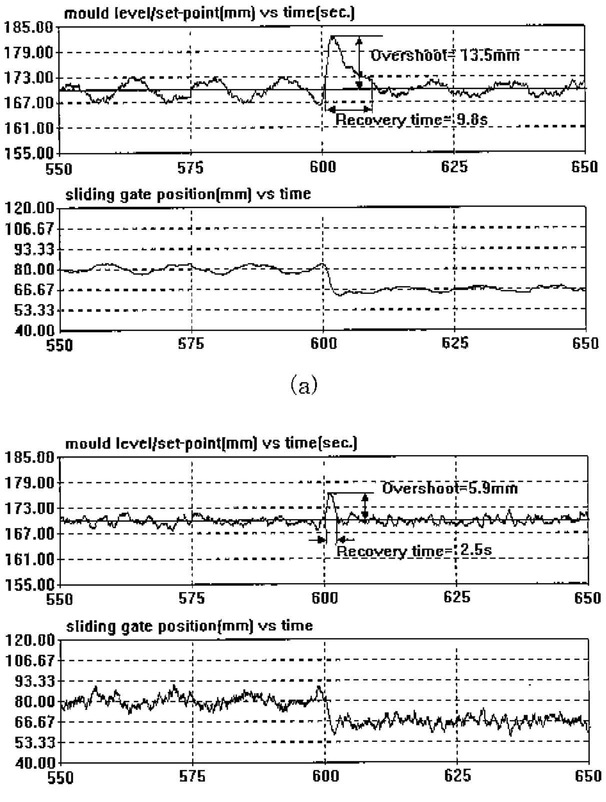
phase, the amplitude and the frequency are changed to the original one. As shown in Fig. 10(a) and (b), the PI controller has larger fluctuation than FLC. This indicates that FLC is more robust to the periodic disturbance than PI controller.

3. Robust to clogging/unclogging

The clogging and unclogging phenomena cause the system time-varying. They reduce, or suddenly increase the inflow rate of the molten steel to the mold without changing the sliding gate position. In this paper, the Clogging/UnClogging(C&UC) is modeled by the change of the coefficient of discharge. Its nominal value is assumed 1.0 and can be decreased by clogging or increased by unclogging. Fig. 10 shows the relation between the inflow rate and the inflow rate with changed coefficient of discharge.

Simulation is done for the C&UC cycle. As shown in Fig. 11, the C&UC cycle consists of a phase of slow clogging followed by a sudden unclogging. Here and are the minimal coefficient of discharge and the clogging time, usually.

The results are given in Fig. 13(a) and (b) assuming s. It is shown that using FLC, the mold level has small fluctuation and fast recovery time compared with that of the PI controller. This demonstrates that FLC is more robust against process parameter variations than PI controller.



(a)

(b)

Fig. 13. Robust of PI & fuzzy controllers against clogging/unclogging. (a) PI control, (b) Fuzzy control.

V. Conclusion

This paper presents a new fuzzy logic control approach for mold level control. It is a PID type hybridizing the conventional PI and PD type fuzzy controllers with a simplified design scheme, it combines the advantages of the conventional PI/PD type fuzzy controllers and overcomes their disadvantages, particularly, it is simple in structure, easy in implementation and fast in computation. Good performance for steady-state response and robust against process parameter variations and disturbances is also observed from simulation. As a result, this control strategy can lead to the improvement of the final cast products. Implementation of the proposed control algorithm in the continuous casting plants is undergoing at POSCO.

References

[1] K. Asano, et al.,"Robust molten steel level control for continuous casting," *Proc. 35th IEEE Conf. on Dec. and Contr.*, vol. 2, pp. 1245-1250, 1996.

[2] G. Bocher, et al., "Slab quality improvement by means of advanced mould level control systems," *MPT International*, vol. 16, no. 3, pp. 50-55, 1993.

[3] R. De Keyser, "Improved mould-level control in a continuous steel casting line," *Control Engineering Practice*, vol. 5, no. 2, pp. 231 237, 1997.

[4] M. Dussud, et al., "Application of fuzzy logic control for continuous casting mold level control," *IEEE Trans. on control system technology*, vol. 6, no. 2, 246-256, 1998.

[5] S. F. Graebe, et al., "Control design and implementation in continuous steel casting," *IEEE Control Systems Magazine*, vol. 15, no. 4, pp. 64-71, 1995.

[6] N. Kiupel, et al., "Improvement of mold-level control using fuzzy logic," *Engineering Applications of Artificial Intelligence*, vol. 7, no. 5, pp. 493-499, 1994.

[7] C. C. Lee, *Fuzzy Logic in Control Systems: Parts I & II, IEEE Trans.* Syst. Man Cybern., vol. 20, no. 1, pp. 404-435, 1990.

[8] H. X. Li and H. B. Gatland, "Conventional fuzzy control and its enhancement," *IEEE Trans. Syst. Man Cybern.----Part B: Cybern.*, vol. 26, no. 5, pp. 791-797, 1996.

[9] M. Mamdani, "Application of fuzzy algorithms for control of simple dynamic plant," *Proc. IEE*, vol. 121, Dec, pp. 1585-1588, 1974.

[10] T. J. Manayathara, et al., "Rejection of unknown periodic load disturbances in continuous steel casting process using learning repetitive control approach," *IEEE Transactions on control system technology*, vol. 4, no. 3, pp. 259-265, 1996.

[11] J. Paiuk, et al., "The automatic mould level control for a continuous casting process, practical imple- mentation of different control algorithms," *Proc. IFAC Automat. in Mining, Mineral, and Metal Processing*, Buenos Aires, Argentina, pp.205-208, 1989.

[12] J. Yen, et al., "Industrial applications of fuzzy logic and intelligent systems," *IEEE Press*, 1994.

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