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Iterative learning control of molten steel level in a continuous casting process

Byungyong You [a], Minsung Kim [a], Dukman Lee [b], Jookang Lee [a], J.S. Lee [a,*]

[a] Department of Electrical and Electronic Engineering, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea
[b] Technical Research Laboratories, Pohang Iron and Steel Co., Ltd., 790-785, Pohang, Republic of Korea

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ABSTRACT

In this paper, an iterative learning control (ILC) method is introduced to control molten steel level in a continuous casting process, in the presence of disturbance, noise and initial errors. The general ILC method was originally developed for processes that perform tasks repetitively but it can also be applied to periodic time-domain signals. To propose a more realistic algorithm, an ILC algorithm that consists of a P-type learning rule with a forgetting factor and a switching mechanism is introduced. Then it is proved that the input signal error, the state error and the output error are ultimately bounded in the presence of model uncertainties, periodic bulging disturbances, measurement noises and initial state errors. Computer simulation and experimental results establish the validity of the proposed control method.

1. Introduction

In continuous casting of steel, controlling the molten steel level is very important because a consistent level increases the surface quality of the final products. However, the level of molten steel in continuous casters is affected by disturbances, time delays and nonlinearities. In a continuous caster, one of the most severe disturbances is bulging, which disturbs the level periodically. Normally, bulging is similar in shape to a superposition of sinusoidal waves and causes molten steel level to oscillate periodically. This paper focuses mainly on eliminating bulging disturbance.

Many strategies have been proposed to control the level of molten steel during continuous casting (Barron, Aguilar, Gonzalez, & Melendez, 1998; Dussud, Galichet, & Foulloy, 1998; Keyser, 1991; Lee, Kueon, & Lee, 2003; Watanabe, Omura, Konishi, Watanabe, & Furukawa, 1999), but none of these attempts to eliminate bulging disturbance directly. Furtmueller and Gruenbacher (2006) modeled the bulging effect and applied it to his control strategy, but this method requires measurement of the current signal of the roller motor under the mold, but this is difficult to obtain in the field and does not properly reflect mold level disturbance due to bulging. Therefore, an iterative learning controller is proposed that can be applied easily to controlling molten steel level.

In a system that is subject to periodic disturbance, the repetitive control method (Doh, Ryoo, & Chung, 2006; Moon, Lee, & Chung, 1998) is often useful. However the repetitive controller needs precise plant information for stability, and large time delay significantly degrades its performance. In contrast, ILC method does not need any plant information, and is easy to implement even in systems that experience large time delay. The proposed ILC technique is responsible for eliminating bulging disturbance while the PID controller mainly stabilizes molten steel level.

This paper is organized as follows. Section 2 derives a mathematical model for molten steel level system; Section 3 describes the proposed controller and the resulting control system; Section 4 shows computer simulation results and Section 5 shows experimental results on 1/4 scale hardware (H/W) simulator; the conclusion is given in Section 6; the stability analysis on the control system is given in the Appendix.

In this paper, the following notations and definitions will be used. $\mathbb{R}^n$ is the n-dimensional Euclidean space with norm $\|z\| = (z^T z)^{1/2}$ for $z \in \mathbb{R}^n$. $C \in \mathbb{R}^{p\times m}$ is a $(p\times m)$-dimensional matrix with real elements and $\|C\| = \sqrt{\lambda_{max}(C^T C)}$ represents the induced matrix norm where $\lambda_{max}(\cdot)$ denotes the maximum eigenvalue. Let $\mathbb{N}$ be the set of positive integers 1,2,…,n. Finally, the α−norm is defined for a positive real function $z : \mathbb{N} \to \mathbb{R}$ as

$$\|z(\cdot)\|_\alpha = \sup_{k\in\mathbb{N}} z(k)\left(\frac{1}{\alpha}\right)^k \quad \text{for } \alpha \geq 1.$$

2. Molten steel level model

In the continuous casting process (Fig. 1), the molten steel in the tundish (Fig. 2) is poured into the mold through a nozzle. The control process is activated to maintain the molten steel level at a preset value. The molten steel is cooled first in the mold, and then

* Corresponding author.
E-mail addresses: ybyvic@postech.ac.kr (B. You), redtoss@postech.ac.kr (M. Kim), drdmlee@posco.co.kr (D. Lee), jklee@postech.ac.kr (J. Lee), jsoo@postech.ac.kr (J.S. Lee).

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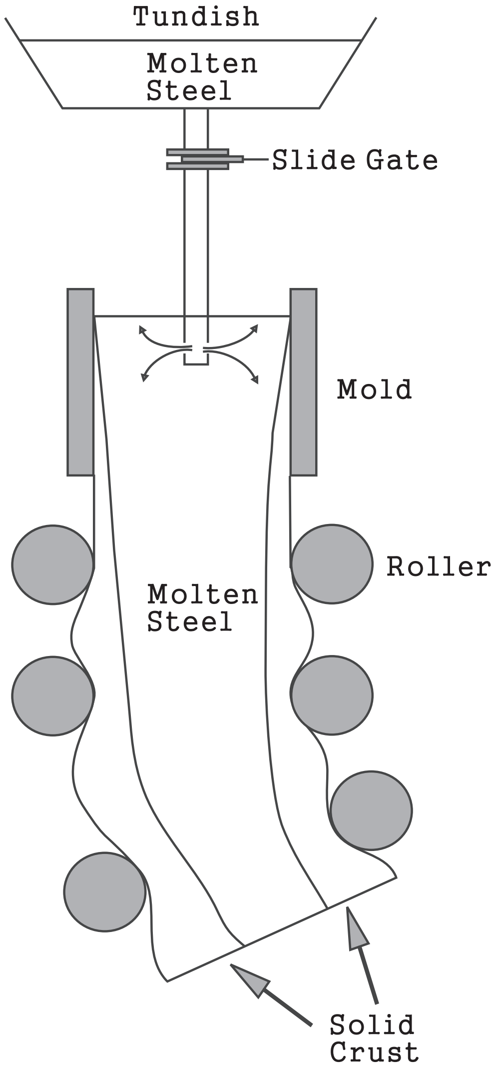

Fig. 1. Continuous casting process.

further by cooling units in the rolls under the mold. Finally the molten steel is shaped into slabs after passing through many rollers.

The continuity equation of the molten steel in the mold is

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

where Q_{in} (m^3/s) is the incoming molten steel flow into the mold, Q_{out} (m^3/s) is the outgoing flow from the mold, and V (m^3) is the volume of molten steel stored in the mold. V is represented as $A \times y$, where A (m^2) is the cross sectional area of the mold and y (m) is the molten steel level in the mold. $A = W \cdot D$, where W (m) is the width of the mold and D (m) is its thickness. Then, Eq. (1) becomes

$$\frac{dy}{dt} = \frac{1}{A}(Q_{in} - Q_{out}), \tag{2}$$

where Q_{in} and Q_{out} are represented as

$$Q_{in} = \sqrt{2gh}SG(u),$$

$$Q_{out} = A \cdot v_0. \tag{3}$$

Here, g (m/s^2) is the gravity acceleration; $\sqrt{2gh}$ is the outgoing velocity of molten steel from the tundish; h (m) is the height of molten steel in the tundish; $SG(u)$ (m^2) is the cross-sectional area through which molten steel flows into the mold and v_0 (m/s) is the casting speed. $SG(u)$ can then be calculated as

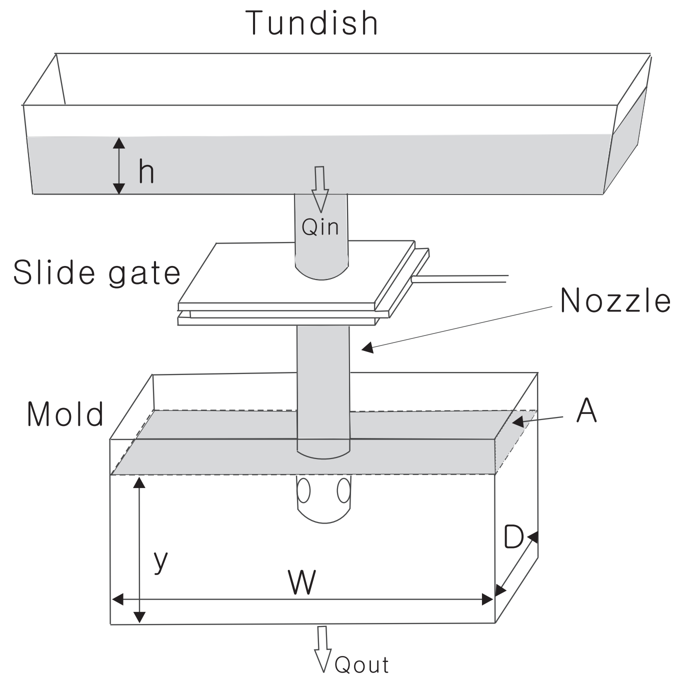

Fig. 2. Tundish and mold.

$$SG(u) = 0, \quad u \le z,$$

$$SG(u) = 4\int_{(u+b)/2}^{u+r} \sqrt{r^2-(x-u)^2}\, dx, \quad u > z$$
$$= \pi r^2 - 2r^2 \arcsin\left(\frac{b-u}{2r}\right) - \left(\frac{b-u}{2}\right)\sqrt{4r^2-(b-u)^2}, \tag{4}$$

where u (m) is the input reference of the slide gate; z (m) is the dead zone; r (m) is the radius of the slide gate; b (m) is the maximum moving distance of the slide gate.

The molten steel level model, (2)–(4) can be described as

$$x_i(k+1) = x_i(k) + B(x_i(k),u_i(k),k) + \beta_i(k) + d_i(k),$$

$$y_i(k) = x_i(k) + n_i(k), \tag{5}$$

where i indicates the number of iterations, k is the discrete time index starting from $k=1$ to $k=n$. For all $k \in \mathbb{N}$, $x_i(k) \in \mathbb{R}^p$, $u_i(k) \in \mathbb{R}^r$, $y_i(k) \in \mathbb{R}^m$, $\beta_i(k) \in \mathbb{R}^p$, $d_i(k) \in \mathbb{R}^p$, $n_i(k) \in \mathbb{R}^m$ are, respectively, the state, the input, the output, the model uncertainty, the periodic bulging disturbance and the output measurement noise at the ith iteration. $B(x_i(k),u_i(k),k)$ is equal to $(\Delta T/A)(\sqrt{2gh}SG(F_{fb}(u_i(k)))-Q_{out})$ where ΔT is the sampling time and $F_{fb}(\cdot)$ is a function of the control input. The molten steel level equation (5) satisfies the following properties and bounds.

Property 1. *A target trajectory for the iterative learning algorithm is given as a bounded output sequence* $y_d(k)$, $k \in \mathbb{N}$, *that can be represented as*

$$x_d(k+1) = x_d(k) + B(x_d(k),u_d(k),k),$$

$$y_d(k) = x_d(k). \tag{6}$$

Property 2. *The function* $B(x_i(k),u_i(k),k)$ *is globally Lipschitz with respect to* $x_i(k),u_i(k)$:

$$\|B(x_1,u_1,k)-B(x_2,u_2,k)\| \le c_B(\|x_1-x_2\| + \|u_1-u_2\|) \tag{7}$$

for all $k \in \mathbb{N}$ *and for some positive constant* c_B.