1. Introduction

Control of molten steel level in continuous casting is important, because it determines the surface quality of the slab. However, regulating the molten steel level is difficult, because it suffers from various disturbances, including variations in casting speed and tundish weight, clogging and unclogging of the nozzle, and bulging disturbance. Among these, bulging disturbance is the most severe. It is created when the supporting rollers push the liquid steel upward periodically. Bulging disturbance is almost sinusoidal in shape and degrades control quality of the molten steel level. Therefore, we focus on removing the bulging disturbance effect from the molten steel level.

Various control strategies have been proposed, including using a disturbance observer to remove disturbances; including using a master slave PID controller in which a slave PID control loop is used inside a master PID control loop to improve the insensitivity to disturbance; using a model-based controller for stable regulation of mold and tundish level; using a neural network model for stopper control to reduce the casting speed variation; using a fuzzy logic controller to remove disturbances; using a notch filter, PID and a fuzzy logic controller to remove disturbances; using an \( H_\infty \) controller to balance disturbance rejection and robust stabilization; using a notch filter and an \( H_\infty \) controller to reduce the amplitude of surface waves.

However, in these papers, the molten steel level dynamics is described with only an integrator and a first-order transfer function, whereas in reality it is more complicated mainly due to time delay in the molten steel level system. In the past, the casting speed and the bulging frequency were relatively low, so the effect of the system delay, which consists mainly of the actuator delay and the sensor delay, was not so serious. However, as the demand for high speed casting process increases, the bulging frequency increases and the phase lag due to the system delay also increases. For example, given the command \( \sin(\omega t) \), the mold response will be \( A \cdot \sin(\omega(t+d) + \theta) = A \cdot \sin(\omega t + \omega d + \theta) \), where \( \omega d \) is the phase lag due to system delay \( d \). So, whenever the casting speed increases, \( \omega \) increases, and the phase lag \( \omega d \) increases even though the system delay \( d \) is fixed. For this reason, the system delay became a crucial obstacle to stabilizing the molten steel level. In this paper, we identify the system delay effect on the disturbance observer as the bulging frequency increases and propose a disturbance observer with time-delay compensation.

This paper is organized as follows. In Chap. 2, the system modeling is derived. In Chap. 3, the proposed controller is presented. The simulation results are presented in Chap. 4. The experimental setup and results are presented in Chap. 5. Finally, conclusion is drawn in Chap. 6.
the cross sectional area of the lower mold, \( V_q \) (\( \text{mm}^3 \cdot \text{s}^{-1} \)) is the casting speed, \( T_a \) (s) is the actuator delay, \( T_f \) (s) is the sensor delay, \( A_d \) (mm) is the amplitude of bulging disturbance, \( W_q \) (\( \text{rad} \cdot \text{s}^{-1} \)) is the frequency of the bulging disturbance, and \( \theta_d \) (rad) is the phase of the bulging disturbance. Consequently, the nominal model of the molten steel level system can be described as in Fig. 3.

3. Disturbance Observer with Time-delay Compensation

As the model of the molten steel level system can be described as an integrator, a first-order transfer function and the system delay, its unit step response becomes unstable. To overcome the problem, we first stabilize the molten steel level system using the PD controller. PD controller works well whenever the system does not have any disturbances, but the molten steel level system suffers from many disturbances. Among these, we need to consider two disturbances: outgoing flow and bulging disturbance. We can easily compensate outgoing flow by adding the integrator to the PD controller (the PID controller), because it is slowly varying around the constant. On the other hand, we cannot compensate the bulging disturbance easily, because it occurs with a frequency of 0.3–0.5 Hz. In this section, we focus on developing a method to reject the bulging disturbance.

If \( Q(s)=1 \) in Fig. 4, the original disturbance observer usually estimates bulging by computing the difference between the control input signal \( n(s) \) and \( P_n^{-1}(s)y(s) \), the response signal of the nominal plant inverse \( P_n^{-1}(s) \) with the plant output \( y(s) \) as the input. Then it feeds this difference back as one of the control input components as in Fig. 4, and, as a result, it eliminates bulging disturbance on the molten steel level.

Assuming that the system delay is negligible, the nominal plant inverse usually comes with the differential terms and hence has the problem of amplifying the noise, so we cannot implement this inverse in its original form. To overcome the difficulty, we multiply the nominal plant inverse with \( Q(s) \) in Eq. 4.

\[ Q(s) \text{-filter design is important to regulate the bulging disturbance.} \]

Our optimized design of the \( Q(s) \) is described as

\[ Q(s) = K_q \frac{1}{s + 8W_q} \cdot \frac{s}{s + 0.05W_q} \]

where \( K_q \) is the \( Q \)-filter gain and \( W_q \) (\( \text{rad} \cdot \text{s}^{-1} \)) is the target frequency.

Since the relative degree of \( Q(s) \) in Eq. 7 is one, we can expect good disturbance rejection, but it has large magnitude in the mid-band frequency range. To overcome the problem, we can add the low pass filter \( (1/(s+5W_q)) \) to Eq. 7, but the resulting filter still suffers from the phase
lag. So we add an additional phase lead controller \((s+0.5W_q)/(s+4W_q)\) to the above filter. Consequently, the resulting \(Q\)-filter as used in Fig. 4 becomes

\[
Q(s) = K_q \frac{s}{(s+8W_q^2)\frac{s^2}{s+0.05W_q}} \frac{s+0.5W_q}{s+4W_q} \quad (8)
\]

As shown in the Bode plot of Fig. 5, this \(Q(s)\) satisfies \(|Q(j\omega)|\approx1\) and \(\angle Q(j\omega)\approx0\) around the disturbance frequency.

The input–output relationship (Fig. 4) is described as

\[
y(s) = G(s)r(s) + S(s)d(s) \quad (9)
\]

where \(G(s)r(s)\) is the command input response and \(S(s)d(s)\) is the disturbance response.

The transfer functions \(G(s)\) and \(S(s)\) are then represented as

\[
G(s) = \frac{C(s)P(s)P_n(s)}{(1 - Q(s))P_n(s) + Q(s)P(s) + C(s)P(s)P_n(s)} \quad (10)
\]

\[
S(s) = \frac{(1 - Q(s))P_n(s)}{(1 - Q(s))P_n(s) + Q(s)P(s) + C(s)P(s)P_n(s)} \quad (11)
\]

where \(C(s), P(s)\) and \(P_n(s)\) represent respectively the transfer functions of the main controller, the real plant and the nominal plant.

We can examine the tracking performance from the command input response and the disturbance rejection performance from the disturbance response. Assuming that \(P_n(s) = P(s)\) and since \(|Q(j\omega)|\approx1\) and \(\angle Q(j\omega)\approx0\) around the disturbance frequency, then we can achieve

\[
G(s) = \frac{C(s)P(s)}{1 + C(s)P(s)} \quad (12)
\]

\[
S(s) = \frac{1}{1 + C(s)P(s)} \quad (13)
\]

\[
C(s) = K_p + \frac{K_i}{s} + K_d s \quad (14)
\]

If we design \(C(s)\) appropriately that makes \(|G(j\omega)|\approx1\) around the command input frequency \(\omega\), we can guarantee tracking and disturbance rejection from Eqs. (12) and (13).

However, in the case of high speed continuous casting process, the system delay plays an important role on the performance of disturbance observer, so we should take the system delay into account in the disturbance observer.

To implement the time-delay compensation mechanism, \(e^{-Te}\) should be added between the plant input and \(Q\)-filter, and \(e^{-Te}\) in the feedback line of the disturbance observer as in Fig. 6. But \(e^{-Te}\) is not physically implementable and we need to implement it by using a time-delay approximator (TDA)\(^{14}\) as follows:

\[
e^{-Te} = \frac{1 + B(s)}{1 + B(s)e^{-Te}} \quad (15)
\]

where

\[
B(s) = \frac{K_p}{1 + K_p s} \quad (K_p > 0) \quad (16)
\]

When \(T_p = T_d\), TDA Eq. (15) will produce good performance whenever \(K_p\) is large, but large \(K_p\) may drive the system unstable because of the feedback through the time delay element. So, it is reasonable to set \(K_p\) not too large to prevent unstability, but Eq. (15) with \(T_p = T_d\) may not be able to approximate \(e^{-Te}\) closely with this \(K_p\). To make Eq. (15) perform better, we tried different values for \(T_p\) and \(K_p\) and draw the Bode plots of Eq. (15) in Fig. 8 with these values. If we applied \(T_p = T_d = 0.24\) s in Eq. (15), which is
the actual time delay value and $K_p=0.1$, 0.2 and 0.3, we obtained almost the same phase lead that is significantly less than the expected phase lead value (25.92 deg) corresponding to the system delay $T_d$. Therefore, we increased $T_p$ up to 0.4 and obtained the desired phase lead as shown in Fig. 8. The gain can rise in the high frequency range due to the increase in $T_p$, but it can be easily solved by arranging the $Q$-filter to have small magnitude in the high-band frequency range.

Figure 7 describes the time delay approximator Eq. (15) and shows how it closely approximates $e^{T_d s}$. As shown in Fig. 7, this TDA very closely approximates $e^{T_d s}$ with $T_d=0.24$ s. this time-delay compensation mechanism significantly improves the tracking and disturbance rejection performance.

4. Simulation

To demonstrate the feasibility and features of the developed controller, we performed various computer simulations where the bulging of 0.3 and 0.5 Hz frequency was tested. In fact, this bulging frequency range occurs in the real thin slab caster.

At first, we compared the simulation results of the existing disturbance observer to those of the disturbance observer (DOB) with time-delay compensation (TDC). However, in general, the time responses of the existing disturbance observer diverge because of the system delay (0.24 s) under the tested bulging disturbances, so we compare the performances of the DOB when $T_p=0$ and $T_p=0.4$ s. In these simulations, we use Eq. (15) for TDC implementation where $K_b=1$ and $K_p=0.1$.

DOB without TDC works normally under the 0.3 Hz bulging disturbance, but it works poorly as bulging frequency increases (Figs. 9(a) and 10(a)). On the other hand, we confirmed that DOB with TDC works well in both cases (Figs. 9(b) and 10(b)).

5. Experiment

5.1. Experimental Setup

We applied the proposed control system to a 1:1 scale hardware simulator (Fig. 11). The controller is implemented in a VME system running at 40-ms sampling interval. The real time operating system that runs on VME is the VxWorks OS from Windriver Systems, Inc., and the proposed controller is programmed using PSET, a programmable logic controller tool.
Figure 11 shows the molten steel level simulator where the water is used instead of actual molten steel. The pump is of hydraulic type, but the stopper and the bulging generator are driven by the electric motors. The hydraulic pump pumps the water stored in the bottom water basin up into the tundish. Then, the water in the tundish is controlled to flow into the mold through the nozzle. The stopper controls the water flow from the tundish to the mold, and the two bulging generators create the bulging disturbance artificially by electrically pumping the water into the mold. The two level sensors measure the mold level, and the flow meter measures the casting speed. The controller receives data from the two level sensors, and sends control input to the stopper through the servo controller.

The molten steel level is measured by the two level sensors. We average the two level sensor outputs and filter the average with the exponential filter. The exponential filter is useful particularly when the level signal suffers from large noise. It is designed as:

\[
y(k) = a \cdot \text{level}(k) + (1-a) \cdot \text{level}(k-1), \quad \text{if} \ |\text{level}(k)-\text{level}(k-1)| > 3 \quad \text{(17)}
\]

\[
\text{level}(k-1) = y(k), \quad \text{if} \ |\text{level}(k)-\text{level}(k-1)| > 3 \quad \text{(18)}
\]

where \( \text{level}(k) \) is the averaged unfiltered molten steel level, \( y(k) \) is the filtered molten steel level, and \( a = 0.03 \).

The PID controller is used for \( C(s) \) in Fig. 4, and its gains are obtained experimentally:

\[
C(s) = 0.12 + \frac{0.04}{s} + 0.0024s \quad \text{(19)}
\]

The time-delay approximator is determined as

\[
e^{0.24t} \approx \frac{1 + B(s)}{1 + B(s)e^{-0.24t}} \quad \text{(20)}
\]

where

\[
B(s) = \frac{1}{1 + 0.1s} \quad \text{(21)}
\]

Other controller parameters were determined based on the actual measurements and system identification techniques and are listed in Table 1.

Table 1. Controller parameter values.

| The controller parameters | Value |
|--------------------------|-------|
| Cross sectional area of the upper mold \( A_s \) (mm\(^2\)) | 125000 |
| Cross sectional area of the upper mold \( A_0 \) (mm\(^2\)) | 31400 |
| Loss factor \( \rho \) | 0.7 |
| Acceleration of gravity \( g \) (mm/s\(^2\)) | 9800 |
| Height of molten steel in the tundish \( H \) (mm) | 2060 |
| Stopper gain \( K_s \) | 156 |
| Amplitude of bulging disturbance \( A_r \) (mm) | 6 |
| Frequency of the bulging disturbance \( f_r \) (rad/s) | 1.88, 3.14 |
| Phase of the bulging disturbance \( \phi_r \) (rad) | 0 |
| Casting speed \( v \) (mm/s) | 106.15 |
| Actuator delay \( T_a \) (s) | 0.2 |
| Sensor delay \( T_s \) (s) | 0.04 |

Fig. 11. 1:1 scale hardware simulator.

Fig. 12. The overview of molten steel level system.

Fig. 13. (a) Molten steel level performance of DOB without TDC. (b) Molten steel level performance of DOB with TDC.

\( C(s) \) is used when Time \( \leq 55 \) s; PID + DOB with or without TDC afterward. The frequency of bulging disturbance is 0.3 Hz. The fine horizontal lines indicate \( \pm 3 \) mm from the 100 mm reference level.
5.2. Experimental Result

We applied the developed DOB to the molten steel level simulator connected with the bulging disturbance generator (Figs. 13 and 14). Under the above parameter settings and 0.3 Hz bulging disturbance, the molten steel level fluctuates ±6 mm periodically with the PID controller, but only ±3.5 mm with the PID plus DOB without TDC. When we applied DOB with TDC to the molten steel level system, the level falls mostly within ±2.5 mm. Moreover, as the bulging frequency increases, the controller performance is degraded with the PID plus DOB without TDC (Figs. 13(a) and 14(a)), but it is maintained with the PID plus DOB with TDC (Figs. 13(b) and 14(b)).

To compare the performance of various controllers numerically, we define the strike rate as

\[ \text{STR} = \frac{n_{\text{strike}}}{n_{\text{total}}} \times 100 \] .......................... (22)

where \( n_{\text{strike}} \) is the number of samples that are within the specified limits (±2 mm, ±3 mm, and ±5 mm), and \( n_{\text{total}} \) is the total number of samples.

We examined the strike rates of various controllers as in Table 2. We usually recommend ±3 mm range, because the surface quality of the slabs is considered well in practical systems when the molten steel level fluctuation is within ±3 mm. We also used ±2 mm range because it is useful to compare the performances of DOB without and with TDC. The DOB with TDC achieves the highest strike rates within ±2 mm and ±3 mm range among the three controllers and can be qualified as a good controller candidate.

6. Conclusion

In this paper, we introduce a DOB with TDC to reduce the bulging disturbance effect on the molten steel level in the continuous casting process. As the processing speed in continuous casting increases, the time-delay in the mold level system becomes serious, but it is effectively compensated with a time-delay compensation mechanism built in DOB with TDC. The performance of the proposed controller has been tested using a 1:1 hardware simulator. The simulation test showed that the bulging disturbance effect on the molten steel level was significantly reduced.

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