PERIODIC DISTURBANCES REDUCTION IN THE CONTINUOUS CASTING PROCESS BY MEANS OF A MODIFIED SMITH PREDICTOR

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Abstract: In the continuous casting process, various control strategies are used to reduce the mold level fluctuations which cause surface defects in the final product. This paper proposes a control structure able to improve the reduction of the bulging effect on the mold level. It is based on the Aström's modified Smith predictor scheme which presents the advantage that the setpoint response is decoupled from the disturbance rejection transfer function. H_∞ control theory is utilized to develop the controller of this second loop. Both the disturbances rejection and the robust stabilization are considered in this design. Effective tuning rules are also given. Simulation results confirm that the proposed design is more effective than the one based on the PID control law currently implemented in several real plants.

1 INTRODUCTION

In the steel industry, the continuous casting is the most used process to solidify the steel. Mold level control strategies are a key factor in ensuring the quality of the final product. Real implementation remains however complex because the controllers have to take into consideration the process uncertainties, the operating point changes and the disturbances affecting the casting. In order to lower the level fluctuations, several control theories have been applied in recent years. Some of them are already implemented at real plants. For example, an adaptive control law has been used to improve the mold level control accuracy (Kurokawa *et al*., 1992). Matoba *et al*. applied the LQ control in the case of low speed casters (Matoba *et al*., 1990). In the present paper, a new control design is proposed aiming at reducing the bulging effect on the mold within a guaranteed delay margin. The performances are compared to those of the currently implemented PID control law.

The paper is structured as follows. Next section describes the continuous casting machine, the phenomena disturbing the casting operations and presents the plant model and the PID control law implemented in the plants. Section III examines the Smith predictor and its modified version. Based on this one, the control structure designed using H_∞ framework is presented. Section IV validates in simulation the proposed structure showing its efficiency compared to PID.

2 CONTINUOUS CASTING MACHINE

2.1 Process Description

As shown in Figure 1, in the continuous casting machine, molten steel flows from the ladle through the tundish into the mold. The steel is solidified in the mold cooled by the water. A solidified shell is thus formed and continuously withdrawn out of the mold until the outlet of the machine where the steel fully solidified is cut into pieces used by different manufacturing processes.

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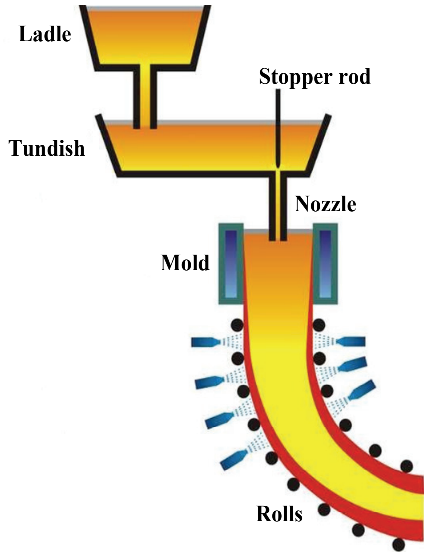

Figure 1: Continuous casting machine.

The steel level in the mold is a balance between the flows in and out of the mold. In order to regulate it, the actuator moves the stopper rod vertically to control the flow into the mold while the casting speed is kept constant. The controller uses also a sensor which measures only local level variations.

During casting operations, several disturbances occur and affect all the parts of the machine including the mold level regulation loop. The following two kinds of disturbances are dominant (Jabri *et al.*, 2008a).

2.2 Disturbances

The main disturbance considered here is the bulging which occurs between rolls due to increasing pressure inside the strand. Its profile is strongly affected by the roll pitch and lightly by the cooling conditions. Unsteady bulging generates important level fluctuations in the mold (Yoon *et al.*, 2002). Frequencies of this phenomenon appear to be in the range of 0.03-0.1Hz.

Other disturbances take place as the slow phase of clogging followed by a sudden unclogging that raises considerably the mold level (Thomas and Bai, 2001). There are also stationary surface waves of molten steel in the mold. Their frequencies depend on the mold width and are between 0.65 and 0.85Hz.

2.3 Plant model

Considering the description above and neglecting the level sensor dynamics, the plant model classically used for the design of the main control law is shown in Figure 2, with P^* the control input, P the stopper position, N the mold level, Q_{in} and Q_{out} the flow-rate into and out of the mold.

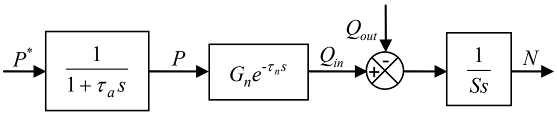

Figure 2: Plant model.

The parameters of the transfer functions appearing in the plant model are: τ_a the actuator time constant, G_n the stopper gain, τ_n the nozzle delay, S the mold section and s the Laplace variable. The process transfer function is thus given by:

$$H = \frac{G_n e^{-\tau_n s}}{Ss(1+\tau_a s)} = H_0 e^{-\tau_n s} \qquad (1)$$

In the plants, the mold level is often regulated by means of a PID controller which is not sufficient for bulging rejection. This current control strategy will be further used for comparison purposes. The tuning parameters are as follows, where the time constant of the derivative action filter is given by T_d/β :

$$K = 0.38 \quad T_i = 9\,\text{s} \quad T_d = 0.2\,\text{s} \quad \beta = 10$$

3 SMITH PREDICTOR CONTROL

3.1 Conventional Smith Predictor

The Smith predictor is widely used for the control of systems with time delays. It is a highly effective dead-time compensator especially for stable processes whose time delay is known (Figure 3).

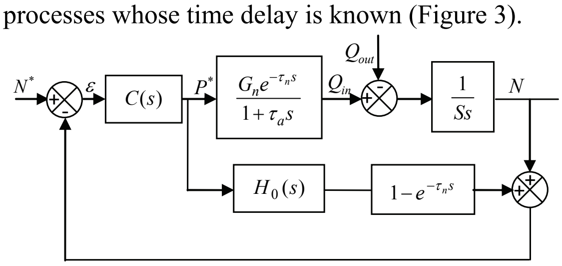

Figure 3: Conventional Smith predictor.

As shown in the equation below where H_0 is the delay free part of the plant model, the main advantage of the Smith predictor is that the delay is eliminated from the closed loop equation:

$$\frac{N}{N^*} = \frac{C(s)H_0(s)}{1+C(s)H_0(s)} e^{-\tau_n s} \quad (2)$$

If the flow out of the mold Q_{out} is equal to zero, the steady state error for a constant setpoint is equal to zero too because the open loop contains an integral term. However, the steady state error imposed by a constant flow out of the mold considered as a disturbance is not equal to zero because at low frequencies, its Laplace transform is given by:

$$\varepsilon_Q(s) = -N = \frac{-C(s)H_0(s)(e^{-\tau_n s}-1)+1}{Ss(1+C(s)H_0(s))} Q_{out} \underset{s\to 0}{\propto} \frac{\tau_n}{S} Q_{out} \quad (3)$$

In order to avoid this problem, several authors have suggested modifications to the original Smith predictor. Lim *et al.,* 1990 proposes an extension based on the introduction of an additional feedback containing $G_n\tau_n$ in parallel with $H_0(s)-H(s)$. Although this structure cancels the steady state error, it does not allow users to tune the disturbances rejection which is a key factor in mold level control. The following paragraph describes the solution proposed by Aström to overcome this problem with the capability of shaping the frequency characteristics of the disturbances rejection (Chen *et al.*, 2007).

3.2 Aström's Modified Smith Predictor

In (Aström *et al.*, 1994), a two-degree of freedom modified Smith predictor is presented for first order integrative processes with dead time as shown in Fig. 4. The Astrom's Smith predictor decouples the disturbance response from the setpoint one and therefore can be independently optimized. Therefore, we can tune the performance of either setpoint tracking (through the transfer function $C(s)$) or disturbance rejection (through the transfer function $M(s)$) without affecting the other.

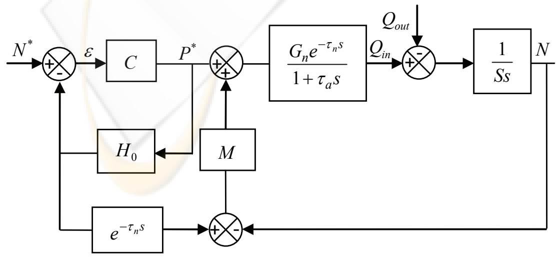

Figure 4: Aström's modified Smith predictor.

In this configuration, the setpoint response is given by:

$$\frac{N}{N^*} = \frac{C(s)H_0(s)}{1+C(s)H_0(s)} e^{-\tau_n s} \quad (4)$$

and the disturbance response is given by:

$$\frac{N}{Q_{out}} = \frac{-1}{Ss(1+MH_0 e^{-\tau_n s})} \quad (5)$$

In this work, the Aström's Smith predictor structure is used to reduce the influence of the bulging on the mold level.

In (Guanghui *et al.*, 2007), the proposed block diagram $M(s)$ is the following where $M_0(s)$ is the transfer function containing the tuning parameters:

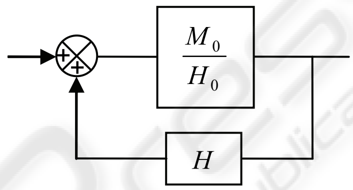

Figure 5: Proposed *M*(*s*) scheme.

Some tuning rules are given for $M_0(s)$ in order to eliminate the steady state error with a step disturbance. Unfortunately, this design does not improve the bulging rejection. Moreover, it uses the identification results of the gain and the delay and depends thus upon uncertainties on these two parameters.

Other simple forms of $M(s)$, e.g. first order function, have been investigated without success. In this paper, H_∞ control theory is used to shape the disturbance response by adjusting $M(s)$. Finally, the main controller $C(s)$ is chosen constant which is sufficient to tune the closed loop response time.

3.3 *M* Design using H_∞ Control Theory

For simplicity reasons, Figure 6 shows only the disturbance rejection loop. In order to achieve the foregoing specifications, a H_∞ control problem, described in Figure 7 and Figure 8, is established (Zhang *et al.*, 1991). A second disturbance W (which represents the standing waves actually) was added to the initial bulging rejection loop to be able to solve the H_∞ problem which requires several assumptions. In the proposed scheme, two weighting functions have been introduced. The first one W_1 is chosen to reduce the bulging effect on the level. The second one W_2 is tuned in order to achieve robust stability under delay changes and uncertainties.

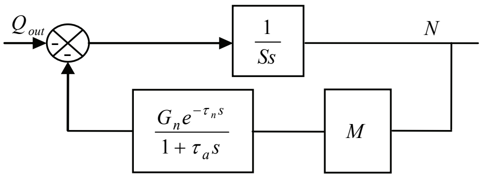

Figure 6: Disturbance rejection loop.

According to Figure 8, it comes:

$$\begin{cases} e_1 = W_1(s)B_{11}(s)Q_{out} + W_1(s)B_{12}(s)W \\ e_2 = W_2(s)B_{21}(s)Q_{out} + W_2(s)B_{22}(s)W \end{cases} \quad (6)$$

$$\text{with } \begin{cases} B_{11} = \frac{-1}{Ss}\frac{1}{(1+MH)} \qquad B_{12} = \frac{1}{1-MH} \\ B_{21} = \frac{-G_n}{Ss(1+\tau_a s)}\frac{M}{(1+MH)} = \frac{-MH_0}{(1+MH)} \\ B_{22} = \frac{G_n}{(1+\tau_a s)}\frac{M}{(1-MH)} \end{cases}$$

Considering the state space formalism of the process described in Figure 7, the H_∞ control problem is formulated as follows:

$$\left\| \begin{pmatrix} W_1(s)B_{11}(s) & W_1(s)B_{12}(s) \\ W_2(s)B_{21}(s) & W_2(s)B_{22}(s) \end{pmatrix} \right\|_\infty \prec \gamma \quad (7)$$

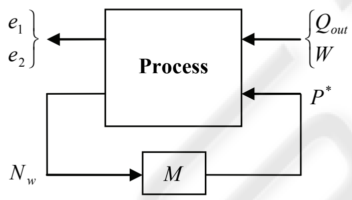

Figure 7: Standard H_∞ problem.

In order to approximate the time delay effect, the first order Pade function is used.

Since the bulging is described by a sinusoidal function with a frequency band between 0.03 and 0.1Hz, $B_{11}(s)$ should have a weak magnitude over this frequency range. First, W_1 is thus selected so that its gain is high over bulging frequencies and high enough on the low frequency band in order to eliminate the steady state error. In this work W_1^{-1} is chosen as a phase lead compensator:

$$W_1^{-1} = K_{w1}\frac{1+T_{w1}s}{1+a_{w1}T_{w1}s} \quad \text{with: } a_{w1} \prec 1 \quad (8)$$

Secondly, W_2 is tuned using the small gain theorem in order to achieve robust stability under delay changes. In fact, if the time delay changes less than $\Delta\tau_n$ (this upper bound is assumed to be known), the bulging rejection loop is stable if:

$$\left\| \frac{-HM}{1+MH}\Delta \right\|_\infty \prec 1 \quad (9)$$

with Δ a multiplicative uncertainty given by:

$$H_a = H(1+\Delta) \text{ and } \Delta = e^{\Delta\tau_n \cdot s} - 1 \quad (10)$$

Knowing that: $|H| = \left|H_0 e^{-\tau_n s}\right| = |H_0|$ (11)

(9) is equivalent to:

$$\left\| \frac{-H_0 M}{1+MH}\Delta \right\|_\infty = \|B_{21}\Delta\|_\infty \prec 1 \quad (12)$$

As Δ satisfies the following inequality:

$$|\Delta(j\omega)| \prec \left| \frac{2\Delta\tau_n \cdot j\omega}{1+\Delta\tau_n \cdot j\omega} \right| \quad (13)$$

W_2 is then chosen as:

$$|W_2(j\omega)| \succ \left| \frac{2\Delta\tau_n \cdot j\omega}{1+\Delta\tau_n \cdot j\omega} \right| \quad (14)$$

The two filters W_1 and W_2 should be calculated from equations (8) and (14). Finally, the H_∞ problem is solved using the Glover-Doyle's algorithm (Glover *et al.*, 1988).

4 SIMULATION RESULTS

The control structure designed in this way is tested by means of a mold level simulator developed with parameters issued from a real plant (Table 1). The previous tuning considers only the bulging rejection. The standing waves rejection was not explicitly taken into account.

Table 1: Plant model parameters.

Parameter	**Value**
τ_a	0.05s
τ_n	0.5s
G_n	10^6 mm^3/s/mm
S	1600×228mm^2
v	1.5m/min

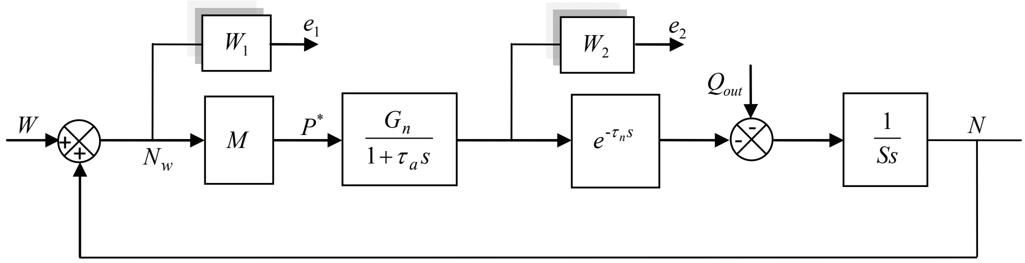

Figure 8: Block diagram of the proposed design.

The weight functions of the proposed design are:

$$W_1 = \frac{1+0.5s}{0.32+1.58s} \qquad W_2 = \frac{2.7s}{1+s}$$

W_2 was selected according to equation (14) in order to achieve a delay margin greater than the identified delay value (0.5s). In this case, the H_∞ controller is given by:

$$M_1 = \frac{27(s+20)(s+4)(s+1)(s+0.57)}{(s+482)(s+9.9)(s+1.2)(s+0.2)}$$

The stability and the robustness of the system controlled by the PID and the Aström's modified Smith predictor can be analyzed using the following diagrams. They show the control laws actions when the bulging occurs.

Figure 9 shows that the bulging rejection transfer function was improved with the modified Smith predictor. However, the steady state error is not equal to zero. In order to overcome this problem, the least of all the poles in M_1 was replaced by zero. Therefore, the new controller is given by (see Figure 10 for the new Bode diagram):

$$M_2 = \frac{27(s+20)(s+4)(s+1)(s+0.57)}{s(s+482)(s+9.9)(s+1.2)}$$

Figure 10 shows that the performances over the bulging frequency band are not modified. Those over lower frequencies are improved.

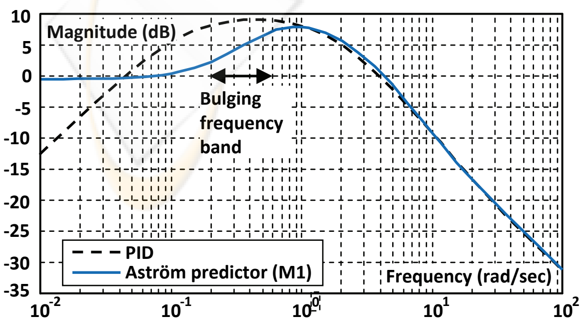

Figure 9: Bode diagram of the bulging rejection (case M_1).

Considering M_2, the main controller C was adjusted to set the closed loop response time ($C=1$). Figure 11 presents results obtained for a level variation of 10 mm.

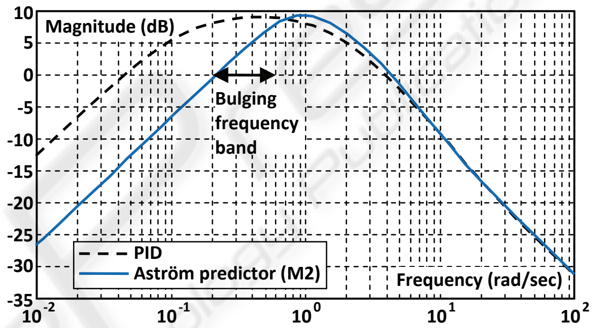

Figure 10: Bode diagram of the bulging rejection (case M_2).

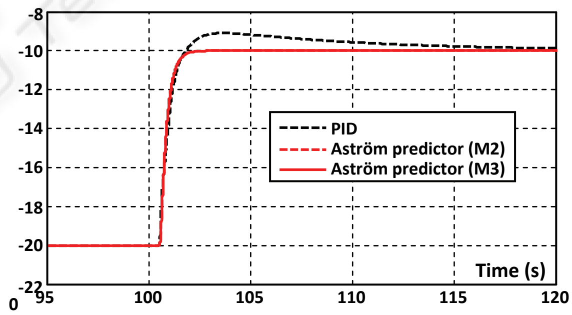

Figure 11: Mold level (mm).

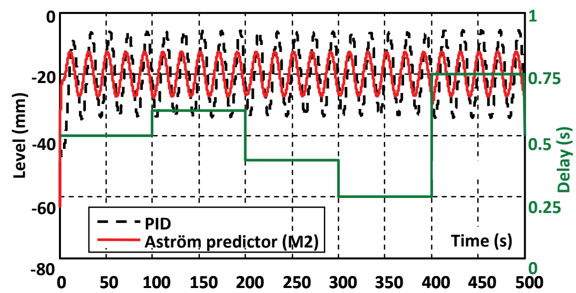

Figure 12: Mold level during bulging when delay changes.

Figure 12 shows the mold level when the delay changes during bulging whose frequency is 0.05Hz. Using M_2, the performances remain better than those of the PID.

M_2 can also be approached by a PID control law (see Figure 13 for the Bode diagrams) as follows:

$$M_3 = 0.51\left(1 + \frac{0.37}{s} + \frac{0.12s}{1 + 0.0025s}\right)$$

Finally, the performances of all the versions of the Aström's modified Smith predictor are summarized and compared with those of the PID in Table 2.

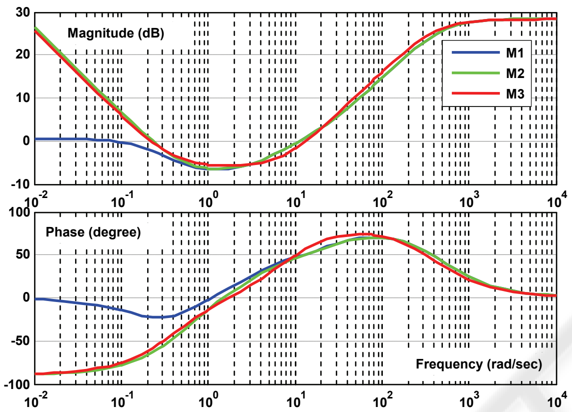

Figure 13: Bode diagrams of all the versions of Aström predictor.

Table 2: Performances of the proposed control laws.

Specifications	PID	Aström predictor		
		M_1	M_2	M_3
Cutoff frequency (rad/s)	1.06	1.3	1.3	1.41
Gain margin (dB)	8.7	10.1	9.9	10.4
Phase margin (°)	66	54	46	42
Delay margin (s)	1.1	0.75	0.61	0.52
$\max_{\omega \in [0.03\ 0.1\text{Hz}]} B_{11}(j\omega)$ (dB)	9	7.2	8.1	7.1
$\min_{\omega \in [0.03\ 0.1\text{Hz}]} B_{11}(j\omega)$ (dB)	8	2	-1.1	-0.6
Steady state error % outflow	0	small	0	0

5 CONCLUSIONS

This paper presents an effective method based on H_∞ control theory combined with the Aström's modified Smith predictor which enhances the disturbance rejection performance compared to the conventional Smith predictor. This one cannot indeed be utilized in the mold level control process since it leads to a steady state error as a response to a step disturbance.

Using simple tuning rules, the level error was reduced compared to the PID control with regards to robust stability. Moreover, this technique allows shaping the disturbance rejection independently from the closed loop response time which is not the case for PID. Further improvements may include additional features as the introduction of observers and feed-forward actions.

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