DISTURBANCES ESTIMATION FOR MOLD LEVEL CONTROL IN THE CONTINUOUS CASTING PROCESS

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Abstract: This paper addresses the problem of mold level fluctuations in the continuous casting process, which strongly penalize the quality of the final product and lead to a costly machine downtime. Therefore, the mold level is controlled using a stopper as the flow control actuator and a level sensor. Under normal casting conditions, the current controllers provide suitable performances but abnormal conditions require manual intervention, such as the decrease of the casting speed, in particular when undesired disturbances like clogging/unclogging or bulging occur. These disturbances increase in severity for certain steel grades or at high casting speeds. Therefore, this paper focuses on the on-line disturbances estimation in order to introduce compensation actions. Starting with the presentation of the continuous casting process, the description of the model of the machine, and highlighting the main control challenges, an observer estimating clogging and bulging disturbances is then developed. This design may help future control architectures based on disturbances estimation. The proposed observer is finally validated by extracting disturbances from experimental signals measured on a continuous casting plant.

1 INTRODUCTION

Nowadays more than 96% of steel is produced by means of a continuous casting process which has significantly improved plant productivity in comparison with other solidification processes. Accurate control of the molten steel level in the mold is an important task from both the operating and quality points of view. Indeed, on the one hand, it is important to control the mold level to avoid molten steel overflows or mold emptying. On the other hand, the mold level must be kept constant to avoid alumina inclusions and slag being caught up in the molten steel, leading to defects associated with cracks in the slabs.

Under normal casting conditions, currently implemented controllers provide suitable performances. However, more severe operating conditions still require manual intervention, such as the decrease of the casting speed, in particular when undesired clogging/unclogging or bulging disturbances occur. These disturbances are in particular extremely sensitive for certain steel grades or at high casting speeds. Therefore, on-line disturbance estimations become an important challenge with a view to introducing feedforward actions within the control law.

The paper is structured as follows. Section 2 describes the continuous casting process and the model of the machine. The design of the observer is presented in Section 3, successively estimating clogging, bulging and both disturbances. The proposed observer is finally validated in Section 4 by estimating disturbances from experimental signals measured on a continuous casting plant.

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2 CONTINUOUS CASTING PLANT MODEL

In the continuous casting process, as shown in Figure 1, molten steel flows from the tundish into the mold through the nozzle where it freezes against water-cooled mold walls to form a solid shell. There are several rolls below the mold to withdraw the solidified steel continuously from the bottom of the mold. The mold has an oscillatory movement with a magnitude of a few millimetres and a frequency of about 2 Hz that makes shell extraction easier. At the outlet of the machine, the steel is fully solidified and is cut into slabs.

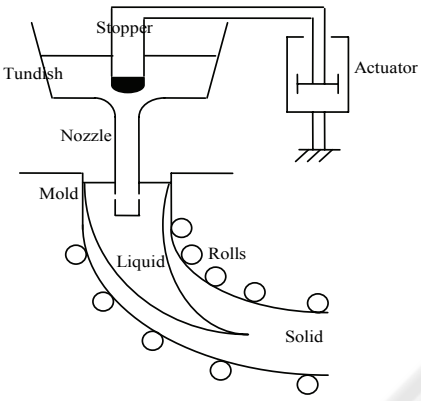

Figure 1: Continuous casting machine.

Usually, the casting speed is kept constant. The flow out of the mold is thus constant and only the inflow is controlled.

Figure 2 shows the major components of the mold level control model without any disturbance that is usually considered in the plants for the design of the control law,

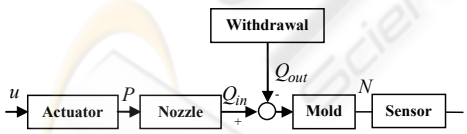

Figure 2: Plant model.

where u is the control input, P the stopper position, N the mold level, Q_{in} and Q_{out} the steel flow-rate into and out of the mold.

This behavioral model shows that the flow into the mold Q_{in} is regulated by the stopper position P by acting on the control input u of a hydraulic actuator. The nozzle is usually modelled in most cases by a simple gain. The flow out of the mold Q_{out} is imposed by the casting speed. The mold level N is thus given by the integration of the difference between Q_{in} and Q_{out} divided by the cross section of the mold. This level is measured by a sensor which can be either an eddy current or a floating one, returning only local level and not the whole free surface feature. Transfer functions appearing in the plant model are summarized in Table 1,

Table 1: Transfer functions of the plant model.

Block	Transfer function
Actuator	$\frac{G_a}{s(1+\tau_1 s)}$
Nozzle	G_s
Withdrawal	$S\ v$
Mold	$\frac{1}{S\ s}$
Level sensor	$\frac{G_{ss}}{1+\tau_2 s}$

where G_s is the stopper gain, G_{ss} the level sensor gain, G_a the actuator gain, S the mold section, τ_n the nozzle delay, τ_1 the actuator time constant, τ_2 the time constant of the level sensor, v the casting speed and s the Laplace variable.

The control objective is to maintain the mold level at a specified constant setpoint while limiting the level fluctuations as much as possible. Implemented controllers use both the level and stopper signals as available measurements and elaborate the actuator input u acting as the manipulated variable. Classic control structures currently working on real plants are of two types: a first structure considers regulation of the mold level with a PID controller; a second one includes two cascaded loops, regulating the stopper position in an inner loop through a proportional gain and the mold level in an external loop by means of a PI controller.

However, the control becomes more complex when disturbances occur on the plant or when the operating conditions change, leading to an unstable behavior. In fact, several phenomena disturb the balance between the flow into and out of the mold, causing fluctuations over the meniscus surface or an abrupt increase of the mold level. The standard controllers are not designed for such casting conditions. Therefore, new control strategies should be designed, for example those based on disturbances rejection. For this purpose, the disturbances must first be estimated on-line so that the control structure can compensate their influence

(Furtmueller and Gruenbacher, 2006). Section 3 will thus consider the design of observers able to estimate the two most important disturbances occurring during continuous casting: the clogging/unclogging and the bulging.

3 DISTURBANCE ESTIMATION

This Section will successively consider observers for clogging/unclogging disturbance, then bulging disturbance and finally for both types.

3.1 Clogging

The clogging event is one of the most serious phenomena faced by the operators in the continuous casting machine. It increases operating cost and decreases productivity. Clogging takes place essentially at the nozzle wall even if in principle it can occur anywhere inside the nozzle. Nozzle clogging takes many different forms. The first one is the sediment of solid inclusions already present in the steel entering the nozzle. The second form is related to air aspiration into the nozzle through joints which leads to reoxidation. The third type of clogging is attributed to reactions between aluminum in the steel and an oxygen source in the refractory. In practice, a given nozzle clog is often a combination of several of these types (Thomas and Bai, 2001). The clogging effect is not an instantaneous phenomenon but develops over time. Its cycle consists of a phase of slow clogging, followed by a sudden unclogging that raises considerably the mold level. Its period is random (Dussud *et al*., 1998).

This part sets out to propose a clogging estimation procedure assuming that this is the only disturbance to arise during the casting operations. Currently, when the clogging occurs, the controller forces the stopper to move to maintain a constant casting speed and a constant level inside the mold. When the unclogging occurs, the flow passage inside the nozzle becomes larger. The stopper position decreases suddenly to reduce the control zone (opening surface) in order to maintain a constant flow rate into the mold. During the clogging/unclogging cycle, the stopper position is thus a succession of ramps. Therefore, a possible model of the clogging/unclogging phenomenon can be the inclusion of an additional flow d_{clog} to Q_{in_ideal} (which is the real inflow without clogging), as in Figure 3. d_{clog} is also a succession of ramps because the flow-rate out of the mold Q_{out} and the level N are generally constant. d_{clog} has thus the same behavior as the stopper position P.

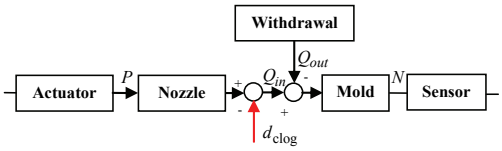

Figure 3: Plant model taking clogging into account.

The observer is designed considering the stopper position P and the casting speed v as inputs, and the mold level N as output. In the following modelling phase, the time constant of the level sensor is ignored, since it influences frequencies out of the bandwidth of the regulation. Without loss of generality, G_{SS} is assumed to be equal to 1. According to the previous figure:

$$S\dot{N} = \underbrace{G_S\,P}_{Q_{in_ideal}} - \underbrace{S\,v}_{Q_{out}} - d_{\text{clog}} \quad \text{with } \ddot{d}_{\text{clog}} = 0 \tag{1}$$

Thus, the clogging model under the state space formalism is given by:

$$\begin{cases} \dot{X}_{\text{clog}} = A_{\text{clog}} X_{\text{clog}} + B_{\text{clog}} U_{c\text{log}} \\ N = C_{\text{clog}} X_{\text{clog}} \end{cases} \tag{2}$$

with:

$$X_{\text{clog}} = \begin{pmatrix} N \\ d_{\text{clog}} \\ \dot{d}_{\text{clog}} \end{pmatrix},\ U_{\text{clog}} = \begin{pmatrix} P \\ v \end{pmatrix},\ C_{\text{clog}}^T = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$
$$A_{\text{clog}} = \begin{pmatrix} 0 & -\frac{1}{S} & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix},\ B_{\text{clog}} = \begin{pmatrix} \frac{G_s}{S} & -1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \tag{3}$$

The observability matrix O_{clog} has full rank 3. The system is therefore completely observable. Based on the model Eq. 2, the Luenberger observer (Sontag, 1998) is given as follows:

$$\dot{\hat{X}}_{\text{clog}} = (A_{\text{clog}} - K_{\text{clog}} C_{\text{clog}})\hat{X}_{\text{clog}} + B_{\text{clog}} U_{\text{clog}} + K_{\text{clog}} N \tag{4}$$

where K_{clog} is the observer gain chosen so that the observer is stable and achieves a desired dynamic. The observer converges if the eigenvalues of the square matrix $A_{\text{clog}} - K_{\text{clog}} C_{\text{clog}}$ are strictly negative. K_{clog} is in a first step chosen to satisfy this condition. The observer is afterwards adjusted with

dynamics as fast as possible, the compromise being that its stability decreases with increasing dynamics.

3.2 Bulging

During the continuous casting process of a slab, the volume of liquid steel inside the solidified shell can be changed by strand bulging in the secondary cooling zone. The bulging occurs between rolls due to increasing pressure inside the strand. It is divided into static or dynamic bulging, according to the strand movement, and steady or unsteady bulging according to the variation with time (Yoon *et al.*, 2002). The most disruptive type is the unsteady bulging generating level fluctuations in the mold.

This part sets out to propose a bulging estimation procedure assuming that this is the only disturbance to arise during the casting operations. It is supposed that the bulging profile at each site between two rolls is described by a sine function (Lee and Yim, 2000) with a frequency between 0.05 and 0.15 Hz. Therefore, this displacement induces changes in the flow-rate out of the mold. The bulging phenomenon can thus be modelled by an additional flow d_{bulge} to Q_{out_ideal} (which is the real outflow without bulging). d_{bulge} is a sum of several sine waves. To determine its frequencies, the level signal spectrum must be calculated and the most significant frequencies belonging to the frequency range selected. In the following part of this subsection, and without loss of generality, only two frequencies of d_{bulge} are considered (see Figure 4).

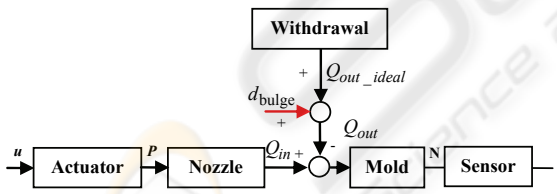

Figure 4: Plant model taking bulging into account.

For the following modelling phase, the time constant of the level sensor is again ignored. According to Figure 4:

$$S\dot{N} = \underbrace{G_S\ P}_{Q_{in_ideal}} - \underbrace{(S\ v + d_{\text{bulge}1} + d_{\text{bulge}2})}_{Q_{out}} \tag{5}$$

with $d_{\text{bulge}\ i} = A_i \cos(\omega_i t + \varphi_i)\ \ i = 1,2$

The bulging model under the state space formalism is thus given by:

$$\begin{cases} \dot{X}_{\text{bulge}} = A_{\text{bulge}} X_{\text{bulge}} + B_{\text{bulge}} U_{\text{bulge}} \\ N = C_{\text{bulge}} X_{\text{bulge}} \end{cases} \tag{6}$$

$$\text{with} \quad X_{\text{bulge}} = \begin{pmatrix} N \\ d_{\text{bulge}1} \\ \dot{d}_{\text{bulge}1} \\ d_{\text{bulge}2} \\ \dot{d}_{\text{bulge}2} \end{pmatrix}, \ U_{\text{bulge}} = \begin{pmatrix} P \\ v \end{pmatrix}$$

$$A_{\text{bulge}} = \begin{pmatrix} 0 & -\frac{1}{S} & 0 & -\frac{1}{S} & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -\omega_1^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\omega_2^2 & 0 \end{pmatrix}, \tag{7}$$

$$B_{\text{bulge}} = \begin{pmatrix} \frac{G_s}{S} & -1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, \ C_{\text{bulge}}^T = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The observability O_{bulge} has full rank 5. The system is thus completely observable. Based on the model Eq. 6, the Luenberger observer is given by the following equation:

$$\dot{\hat{X}}_{\text{bulge}} = (A_{\text{bulge}} - K_{\text{bulge}} C_{\text{bulge}}) \hat{X}_{\text{bulge}} + \\ + B_{\text{bulge}} U_{\text{bulge}} + K_{\text{bulge}} N \tag{8}$$

where K_{bulge} is the observer gain adjusted as in Section 3.1.

3.3 Clogging and Bulging

The previous clogging and bulging observers were designed separately to estimate respectively clogging or bulging being the only disturbance acting on the system. However, when clogging and bulging occur simultaneously during the continuous casting operation, these two observers must be merged into a single global one that will be able to estimate d_{clog} and d_{bulge} individually (Figure 5).

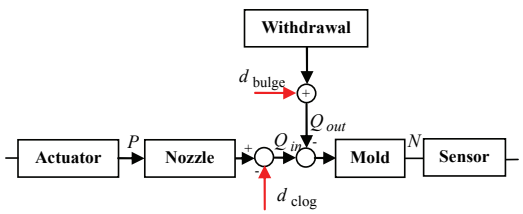

Figure 5: Plant model with clogging and bulging effects.

With this figure, merging Eqs. 1 and 5 leads to:

$$S\dot{N} = \underbrace{G_S\ P - d_{\text{clog}}}_{Q_{in}} - \underbrace{(S\ v + d_{\text{bulge}})}_{Q_{out}}$$
$$\text{with}\ \ \ddot{d}_{\text{clog}} = 0 \qquad (9)$$
$$d_{\text{bulge}} = d_{\text{bulge}1} + d_{\text{bulge}2}$$
$$d_{\text{bulge}\ i} = A_i \cos(\omega_i t + \varphi_i)\ \ i = 1,2$$

which results in the global clogging/bulging model under the state space formalism:

$$\begin{cases} \dot{X}_{est} = A_{est} X_{est} + B_{est} U_{est} \\ N = C_{est} X_{est} \end{cases} \qquad (10)$$

with:

$$X_{est}^T = \left(N\ \ d_{\text{clog}}\ \ \dot{d}_{\text{clog}}\ \ d_{\text{bulge}1}\ \ \dot{d}_{\text{bulge}1}\ \ d_{\text{bulge}2}\ \ \dot{d}_{\text{bulge}2}\right)$$

$$A_{est} = \begin{pmatrix} 0 & -\frac{1}{S} & 0 & -\frac{1}{S} & 0 & -\frac{1}{S} & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -\omega_1^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -\omega_2^2 & 0 \end{pmatrix} \qquad (11)$$

$$U_{est} = \begin{pmatrix} P \\ v \end{pmatrix},\ B_{est} = \begin{pmatrix} \frac{G_s}{S} & -1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix},\ C_{est}^T = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The observability matrix O_{est} has full rank 7. The system is thus completely observable. Based on the model Eq. 10, the global Luenberger observer is given by the following equation, where K_{est} is the observer gain adjusted as previously:

$$\dot{\hat{X}}_{est} = (A_{est} - K_{est} C_{est})\hat{X}_{est} + \\ + B_{est} U_{est} + K_{est} N \qquad (12)$$

The generalization to more than two frequencies taken into account in the bulging disturbance is performed by considering two additional state variables per added frequency, with adequate rows and columns in the state representation. It must be noticed that, due to the observer structure, the average of the d_{bulge} signal is included in the estimation of d_{clog}. In short, d_{clog} contains the average of d_{bulge} and a succession of ramps possibly.

4 OBSERVER VALIDATION

The previous global observer is now applied on experimental data registered during continuous casting operations. A first experiment is considered (record 1), for which the eigenvalues of the observer have been tuned (according to bulging signal frequencies) to −1.5, −1.57, −1.27, −1.42, −1.35, −1.2 and −1.12. Results are given in Figures 6 and 7. Figure 6 compares the estimated d_{bulge} to Q_{out_ideal}. Q_{out_ideal} appears to be ten times greater than d_{bulge}. It can be concluded that there is no bulging effect in this first record.

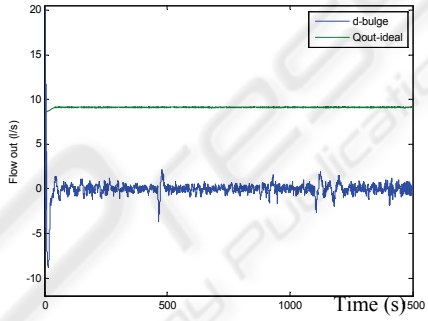

Figure 6: Comparison between the estimated d_{bulge} and Q_{out_ideal} in the case of the first record.

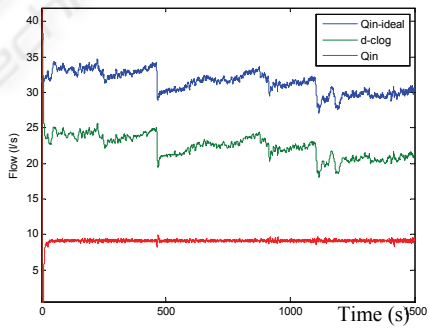

Figure 7: Comparison between the estimated d_{clog}, the ideal and the real input into the mold for the first record.

Knowing this, Figure 7 now compares the estimated d_{clog} elaborated by the observer with the ideal (Q_{in_ideal}) and the real (Q_{in}) input into the mold in the case of this first record. Q_{in_ideal} is recomputed by means of the measurement of the stopper position P as mentioned in Eq. 5 and Q_{in} is recalculated by means of the relation in Eq. 9. It is shown that the estimated clogging disturbance follows the expected profile, i.e. ramp variations during the clogging phase and a sudden decrease due to unclogging. This figure also illustrates that Q_{in} is three times smaller than the ideal value Q_{in_ideal}

expected without clogging. Thus this estimation by means of an observer, which may be useful for control purposes, also helps to quantify the intensity of the clogging phenomenon.

The observer, tuned as previously, is now applied to a second experiment (record 2). In this case, three frequencies of the signal d_{bulge} have to be considered, respectively 0.084, 0.095 and 0.082 Hz as the most significant in the bulging frequency range [0.05, 0.15] Hz.

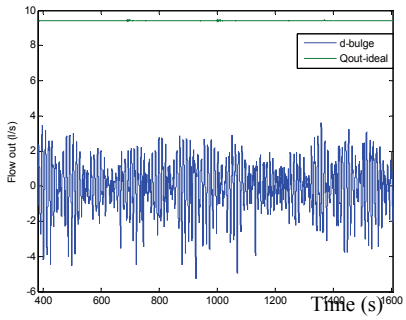

Figure 8: Comparison between the estimate d_{bulge} and Q_{out_ideal} in the case of the second record.

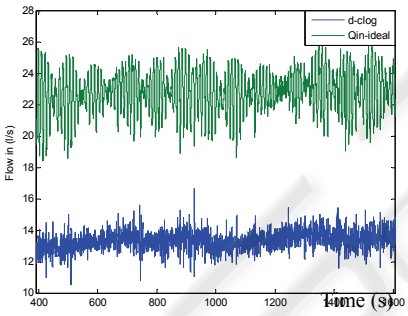

Figure 9: Comparison between the estimated d_{clog} and Q_{in_ideal} in the case of the second record.

Figures 8 and 9 show the estimated disturbances d_{bulge} and d_{clog}. Figure 9 compares the estimation of d_{clog} to Q_{in_ideal}. Without ramp in d_{clog}, it can be concluded that d_{clog} only represents the average of the d_{bulge} signal of Figure 8 which should be added to it in order to estimate its correct value, and that there is no clogging effect in this record. From a control point of view as described in (Furtmueller *et al.*, 2005), to have the average of d_{bulge} included in d_{clog} is not problematic. In fact, the control structure which compensates disturbances should use the sum of d_{clog} and d_{bulge} as an input and not the two disturbance estimations separately.

5 CONCLUSIONS

This paper presents the elaboration of a global observer designed to estimate clogging and bulging disturbances appearing in a continuous casting process. These estimations may be further used as inputs to compensation modules within mold level control structures. This observer is built with behavioral models of the physical process, assuming that these disturbances can be modelled as exogenous signals. Further research may consider a nonlinear nozzle gain to model the clogging effect, robustness analysis of the estimator, particularly with respect to variations of the bulging signal frequencies and model uncertainties.

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