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Robust Mould Level Control

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Abstract— **In the first years of production since 2000, the caster of the Direct Sheet Plant in IJmuiden experienced unstable oscillations in the control of the mould level. This paper reports on the research that was conducted to find the cause of and solution for this problem. For that purpose, a 1:1 scale water model was used. From this scale model, it appeared that the oscillations were due to surface waves induced by stopper movements. To model the effect of the surface waves, a simple standard simulation mould level model was extended by a heuristic wave model. Using this model, a robust stable mould level controller was designed. This new controller has proven to be successful since its implementation in 2002.**

I. Introduction

THe Direct Sheet Plant (DSP) of Corus, located in IJmuiden, produces steel strip coils directly from liquid steel. Figure 1 schematically shows the main processes in the DSP. In the DSP caster liquid steel is cast continuously into a strand which is transported via the tunnel furnace to the reduction mill.

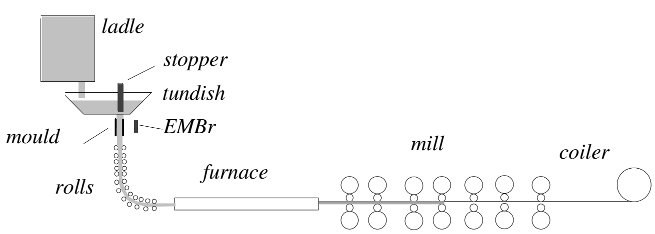

Figure 1 Schematical layout of the Corus Direct Sheet Plant.

The casting process plays an important role in achieving good quality steel and a high production level. When casting, liquid steel is poured into the tundish from the ladle; the steel flows through an opening in the bottom of the tundish and a Submerged Entry Nozzle into the mould. Above this opening a stopper is positioned. The stopper height (i.e. distance between stopper and opening) determines the liquid metal flow. The steel velocities in the mould are reduced by the Electro-Magnetic Brake (EMBr). From the bottom of the mould the strand (with a solidified shell and liquid core) is pulled down by the rolls. The mould level is measured by a radiometric sensor and fed back to the mould level controller which adjusts the stopper height in order to maintain the mould level at target level. Good steel quality and reliable caster operations require the mould surface to be flat and kept within a specific window, and fluctuations to be reduced as much as possible. Fluctuations can result in excessive rim formation and infiltration of lumps of molten casting powder in the liquid steel that might be entrapped in the solidifying shell. This can result in surface defects in the final strip product and/or irregular heat transfer from the strand to the mould; the latter can cause cracks in the shell that leads to a breakout. In case of a breakout, liquid steel flows through the crack. After a breakout, casting is stopped and the plant must be repaired which can take 8-12 hours. To avoid these problems the DSP requires that mould level fluctuations are to remain smaller than 3 mm, as much as possible.

The mould level variations can be reduced by the EMBR and the mould level controller. After production started in 2002, the caster suffered from inadequate mould level control, in particular during startup of casting. Figure 2 shows an example of a startup. The mould is filled up using a PI controller, which is destabilising and causes large mould level oscillations at a frequency of 3 rad/s. At t = 17s, control switches to PID with a Notch Filter (the details of which will be described in section III), but the oscillations remain. These oscillations, and oscillations at frequencies of 7 and 9 rad/s, were occurring almost every time when starting up at a casting width of 1350 mm or above.

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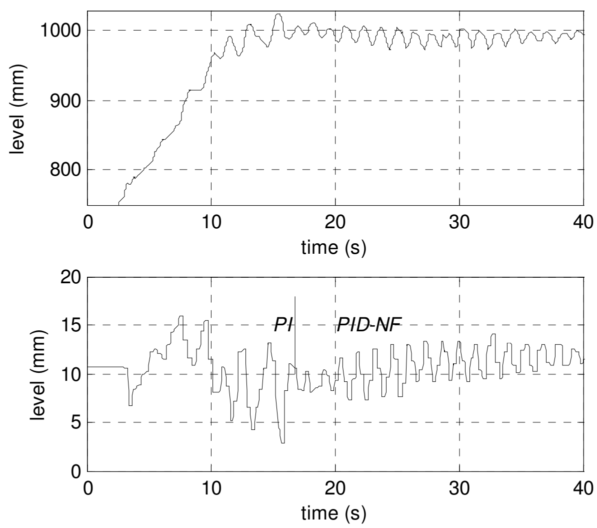

Figure 2 Mould level (upper graph) and stopper position (lower graph). Control switches from PI to PID-NF at t=17s. Mould level fluctuations exceed 20 mm.

After a couple of breakouts that were caused by these oscillations, several operational measures were taken. First, it was decided not to start casting wider than 1350 mm. Second, casting was stopped as soon as the oscillations appeared (to avoid a breakout). To solve the problem, research aimed at improving mould level control was initiated.

The problem of designing a mould level controller is not new. In [1], [4] and [5] adaptive controllers are presented that overcome the variations in the dynamics that are due to clogging and wear of the stopper tip (or valve surface). Instead of adaptive control, fuzzy or H_8 control is applied in [2], [3] and [6], for the same reasons. In [7], the controller is extended by a feedback compensation for periodic disturbances. In all of the aforementioned publications, the dynamics of the mould level are described using a simple mass balance, while in reality the dynamics are much more complicated due to surface waves. As will be shown in section II of this paper, the effect of surface waves could not be ignored in the design of a controller for the DSP.

This paper reports on the research into the DSP mould level control problem. Section II reports the efforts to model the mould level dynamics. Section III describes how a new controller was designed. The results of this controller are presented in section IV.

II. MODELING OF THE MOULD LEVEL DYNAMICS

The problem of mould level oscillations with increasing amplitude, as noted in the DSP, indicates that the feedback control loop is unstable. To investigate the cause of instability, a model of the closed loop was needed. The lumped mould level model that is usually presented in literature on mould level control (see e.g. [1]-[7]), is based on a simple mass balance (increase of mass per second = net inflow of steel):

$$h = \frac{1}{Mb\,s} q_{in} + d = P(s) q_{in} + d \tag{1}$$

with M the mould width (m) with values between 1.0 - 1.5 m for the DSP, b = 0.07 m the mould thickness, s the Laplace variable, h the mould level variations around steady state (m), q_{in} the inflow of steel into the mould (m^3/s), d the disturbance (m^3/s). The model described by (1) will be referred to as the Integrator model.

The disturbance d in (1) can in principle be modeled as integrated white noise, although occasionally periodic disturbances may occur, as well as impulse-like disturbances. The inflow q_{in} is mainly determined by the stopper height, which is controlled by a slave controller that adjusts a hydraulic actuator. The relation between stopper reference height and inflow can be modeled as:

$$q_{in} = \frac{K}{(0.1s+1)^2} u = H(s) u \tag{2}$$

with K the stopper gain mm^2/s, u the stopper reference height (m) and s the Laplace variable. The stopper gain values vary during casting. Its value cannot be measured directly, but it can be estimated indirectly from measurements of the caster speed, mould level and stopper position. According to our estimations the values of K usually vary between 0.5 - 1.5 m^2/s.

The mould level sensor introduces dynamics and noise; the latter is due to the fact that the measurement is based on counting radiation particles. The sensor dynamics can be modeled as

$$y = \frac{e^{-\tau s}}{0.3s+1}(h+n) = F(s)(h+n) \tag{3}$$

with y the measured mould level (mm), n white noise (mm) with random distribution and a variance of 1.5 mm, τ a time delay (s). The time delay is believed to be introduced by the sensor; its value is not certain, but is thought to be somewhere in the range 0 - 0.15 s.

Figure 3 shows a block-diagram of the plant model, defined by (1), (2) and (3).

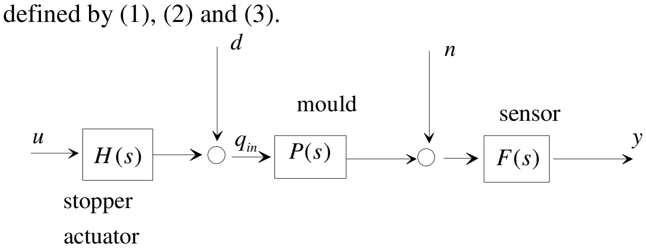

Figure 3 Block-diagram of mould level model.

The control input u is adjusted by the mould level controller according to:

$$u = C(s)\left(r - y\right)$$

with r the reference level (m)

The controller C(s) used in 2000, consisted of a PID controller according to

$$C(s) = 0.13 + \frac{0.03}{s} + \frac{0.025s}{0.05s+1} \qquad (4)$$

This controller was later extended by a notch filter N(s) placed in series with the PID controller, according to

$$N(s) = \frac{s^2 + 0.2815s + 49.5217}{s^2 + 2.815s + 49.5217} \qquad (5)$$

The notch filter has a notch at 7 rad/s. The closed loop model, described by equations (1)-(5) does not explain the instabilities as observed in the DSP. Even if the gain K is increased until instability occurs (K > 30), the oscillation frequency is far from the observed instability-frequencies (3, 7 and 9 rad/s).

Hence, a more detailed model of the mould level dynamics was needed. For that purpose, use was made of a full scale water model of the caster. The open loop dynamics of the scale model were investigated by varying the stopper height sinusoidally. In contrast to the DSP, the dynamics of the stopper actuator and the sensor, and the sensor noise can be ignored. For the water scale model, the Integrator model becomes

$$y = \frac{9}{s}u \qquad (6)$$

Figure 4 shows a Bode diagram of measurements of the scale model and the Integrator model.

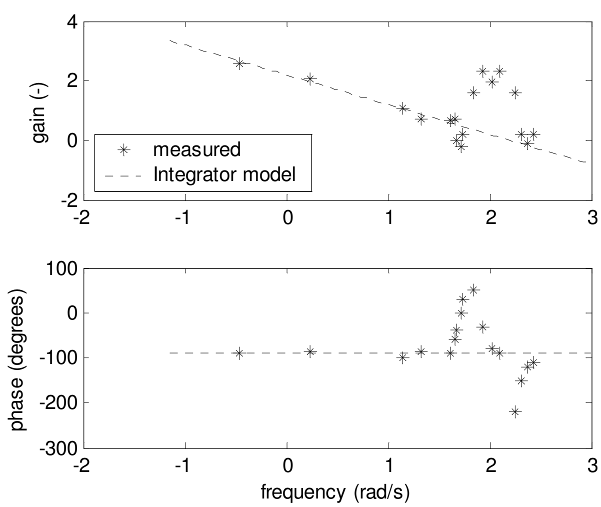

Figure 4 Bode diagram of measurements and Integrator model

For frequencies below 1.5 rad/s, the Integrator model is correct, but for higher frequencies the gain of the scale model shows resonance peaks. These peaks appeared to be due to standing waves in the fluid. In [8] the frequencies ω_k (rad/s) of standing waves are estimated at

$$\omega_k = \sqrt{\frac{k\pi\, g}{W}}, \quad k = 1, 2, 3, \ldots$$

These frequencies agree well with the measured resonance frequencies in the scale model. According to [9], the amplitude of the standing wave, depends sinusoidally on the position of the sensor, as shown in figure 5 for the case of a standing wave corresponding to k=2.

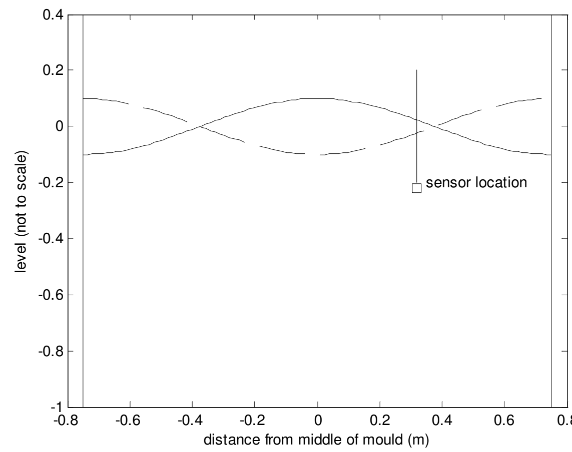

Figure 5 Extreme surface lines (solid and dashed) of standing wave corresponding to k=2, and sensor location.

In the water model only the standing waves corresponding to k=2 and k=4 were observed. To model these standing waves, the Integrator model was extended by a transfer function *W(s),* according to

$$h = P_w(s)q_{in} + d$$

$$P_w(s) = \frac{1}{Mbs} + W(s) \qquad (7)$$

The transfer function W(s) is defined by

$$W(s) = \sum_{k=2}^{4} \frac{2A_k B_k \omega_k\, s}{s^2 + 2B_k \omega_k s + \omega_k{}^2} \qquad (8)$$

with

$$A_k = K_k \cos\left(\frac{2\pi x}{M}\right)$$

$$B_k = 1/(\tau_k \omega_k)$$

x= distance of sensor from middle of mould (m)

The parameters K_k (-) and τ_k (s) were fit to measurements obtained from the water model; the values obtained were

$$K_2 = 60, \quad K_3 = 0, \quad K_4 = 15, \quad \tau_2 = 8, \quad \tau_4 = 6.5$$

Figure 6 shows how the model fits the measurements. The agreement is remarkable, considering that the extension of W(s) was not based on physics.

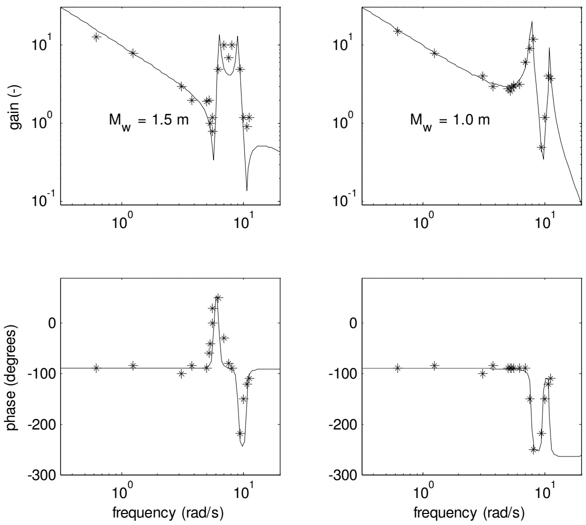

Figure 6 Comparison of measurements from the scale model and Integrator model (1) extended by (6).

The closed-loop model defined by (1)-(8) is unstable if the stopper gain K exceeds a value around 2 or larger. Depending on the mould width, the level can show undamped oscillations corresponding to the frequency ω_2 and ω_4. As these frequencies were also observed in the DSP, the standing waves seemed to explain the instabilities, except for the oscillations at ω_1. These oscillations indicate that in the DSP the k=1 wave does occur, even though it does not occur in the scale model. The fact that these oscillations sometimes do occur, and sometimes not, indicates that the parameters K and K_k are not certain. Using the model presented in this section, the mould level controller was redesigned.

III. CONTROLLER DESIGN

As argued in section II, the mould level dynamics can be described by (1) - (6), but with parameters that vary with time and that are not certain. The H_∞ loop shaping design technique was applied since uncertainties can be taken into account in a systematic way, as will be shown next.

Figure 7 shows the nominal plant model, modeled by equation (1), extended by weighting filters $V_n(s)$, $V_d(s)$ and $W_h(s)$.

The H_∞ controller was obtained by minimising γ in the inequality

$$\|G(s)\|_\infty \le \gamma \qquad (9)$$

with G(s) defined by

$$G(s) = \begin{bmatrix} T_0 V_n & S_0 V_d \\ W_h R_0 V_n & W_h R_0 V_d \end{bmatrix}$$

with

$$T_0 = L_0(1 - L_0)^{-1},\ S_0 = (1 - L_0)^{-1},\ R_0 = CF(1 - L_0)^{-1}$$

$$L_0 = P_0 HCF$$

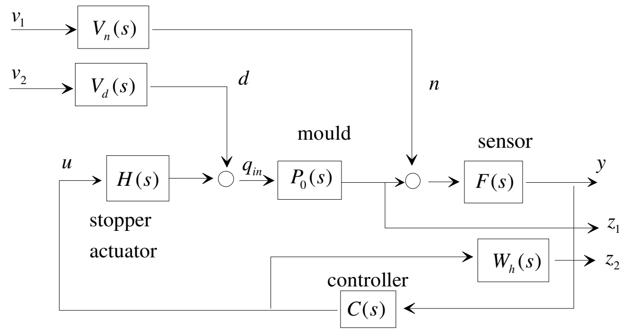

Figure 7 Block-diagram of the model used in the design of the H_∞ controller.

In fact, G(s) describes the transfer function from v_1 and v_2 to z_1 and z_2, i.e.:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = G(s) \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

The following implication was used in choosing the weighting filters (in particular the filter $W_h(s)$):

$$\|G(s)\|_\infty \le \gamma \ \Rightarrow\ \|G_{ij}\|_\infty \le \gamma \quad i, j = 1, 2 \qquad (10)$$

The weighting filter gain of $V_n(s)$ was chosen almost 1 since the noise level is constant, except for high frequencies (above 10 rad/s) where the gain has been increased to avoid numerical computation problems. The weighting filter $V_d(s)$ was chosen as a "near" integrator since disturbances d can be considered as integrated white noise (see section I). An exact integrator could not be used as the system is then not stabilisable; to avoid this, the pole of $V_d(s)$ is not chosen at zero, but slightly negative.

The transfer function $W_h(s)$ is chosen such that robust stability is guaranteed if $\gamma < 1$ is achieved. To explain how this transfer function has been chosen, the small gain theorem is stated here first.

Theorem 1 (Small Gain Theorem)

Consider the interconnection shown in Figure 8. Assume that both the nominal system B(s) and the perturbation $\Delta(s)$ are stable, then the closed loop is stable for all perturbations $\Delta(s)$ if and only if $\|B\Delta\|_\infty < 1$

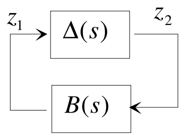

Figure 8 Interconnection of a stable transfer function B(s) and an uncertain perturbation block $\Delta(s)$

Figure 9 shows the plant model of the DSP, extended by a perturbation block $\Delta(s)$ that represents the uncertainty.

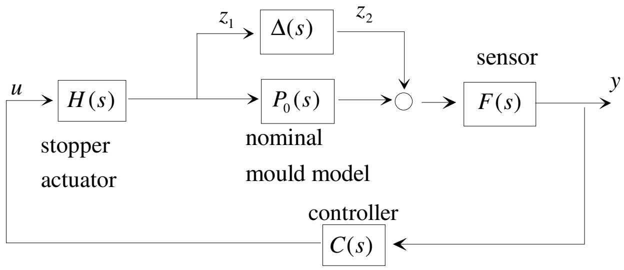

Figure 9 DSP model extended by perturbation block $\Delta(s)$ (additive uncertainty model).

The mould dynamics is thus modeled by the so-called additive uncertainty model

$$P(s) = P_0(s) + \Delta(s)$$

with $\Delta(s)$ the perturbation block and $P_0(s) = \dfrac{1}{M_0 b_0 s}$ the nominal mould model with M_0 = 0.125 m, b_0=0.09 m.

According to the Small Gain Theorem, the condition for robust stability is that the transfer function from z_2 to z_1 in Figure 9 is stable and that its product with $\Delta(s)$ has infinity norm smaller than 1. The transfer function $B(s)$ from z_2 to z_1 is given by:

$$B(s) = \frac{H(s)C(s)F(s)}{1 - L_0(s)}$$

Hence, for robust stability, the product of this transfer function with the perturbation block $\Delta(s)$ must have an infinity norm smaller then one:

$$\left\| \frac{HCF}{1-L_0} \Delta \right\|_\infty \le 1$$

If the H_∞ design has been completed, inequality (10) is satisfied, i.e.:

$$\left\| W_h \frac{CF}{1-L_0} V_d \right\|_\infty \le \gamma$$

Hence, by choosing

$$\|W_h\|_\infty > \left\| \frac{\Delta(s)H(s)}{V_n(s)} \right\|_\infty = \left\| \frac{\left[P(s) - P_0(s)\right]H(s)}{V_n(s)} \right\|_\infty \qquad (11)$$

robust stability is guaranteed if γ<1

Condition (11) is equivalent to

$$\left|W_h(j\omega)\right| > \left| \frac{\left[P(j\omega) - P_0(j\omega)\right]H(j\omega)}{V_n(j\omega)} \right| = \left|P_{err}(j\omega)\right| \quad \forall \omega > 0 \qquad (12)$$

with ω the radial frequency (rad/s). The weighting filter W_h has been chosen such that condition (12) was satisfied for different mould dynamics models of P(s) including the wave dynamics, i.e. defined by equation (7), but for widths M between 1 and 1.5 m. Figure 10 shows graphs of the gain of W_h and gains of $\left|P_{err}(j\omega)\right|$. As can be seen, the weighting filter is chosen somewhat conservative at higher frequencies to be on the safe side. At low frequencies the gain of the weighting filter seems to be insufficient, but that appeared not be the case in simulations.

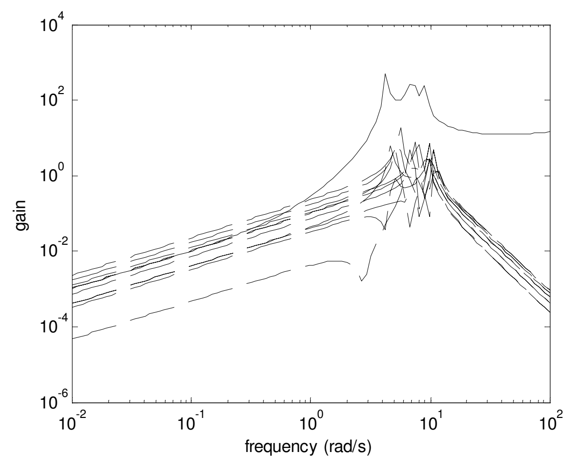

Figure 10 Graphs of the gain of the weighting filter W_h (solid line) and the gains of $\left|P_{err}(j\omega)\right|$ as given in (12) for various mould widths (dashed lines).

To achieve γ<1, the gain of the weighting filter V_d was varied.

The resulting H_∞ controller (of 10th order) was implemented as a series connection of 5 standard second order transfer functions in the GE control software of the DSP.

IV. Results

The H_∞ controller was first tested in December 2002 and has been in use ever since. Figure 11 shows the mould level and stopper position during a startup of casting in 2003. The mould is filled first, during which a PI controller is used. As soon as control switches to the H_∞ controller, the controller stops reacting to the oscillations, and they dampen. The H_∞ controller has been tested for all mould-widths and appeared to function satisfactorily. Since its implementation, unstable oscillations have not been observed anymore. Because of its reliability, the limitation on mould-width has been abolished, production has increased significantly and the number of breakouts per month has reduced.

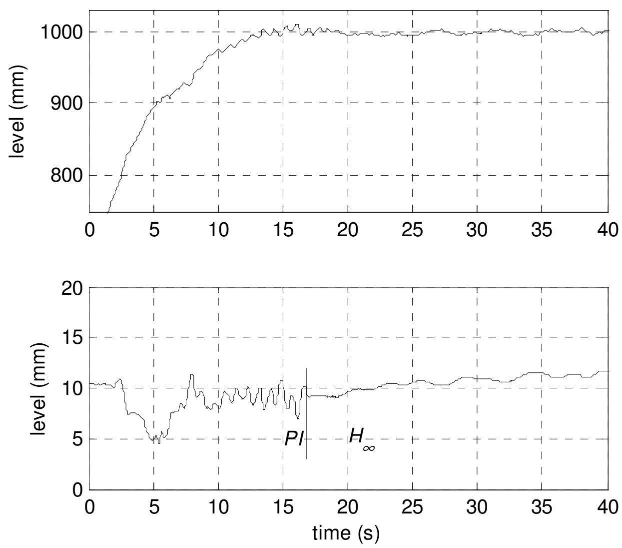

Figure 11 Mould level (upper graph) and stopper position (lower graph). Control switches to H_∞ at t=17s.

V. Future research

The dynamics of the mould level, in response to stopper movements are not yet fully understood. The physical scale model has helped to clarify the fact that standing waves can occur, but it is not yet clear what causes them, and how they are influenced by caster speed and the EMBr. Further research is required to increase our understanding of the mould level dynamics. With more knowledge of the system, the controller can be tuned more tightly, leading to improved control.

Acknowledgment

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