Periodic Disturbance Suppression in a Steel Plant with Unstable Internal Feedback and Delay

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***Abstract* - During continuous casting, especially of modern steel grades or at higher casting velocities, undesired oscillating disturbances may occur, which strongly impair the quality of the final product, or even lead to costly plant downtime. In this paper, both a novel model based explanation of these level oscillations in terms of unstable internal feedback and delay time, as well as a corresponding control to reject the oscillations are presented. The first part of the paper shows how these oscillations arise from couplings inside the strand and how they can be explained in terms of approximated periodic oscillations. To this end, both a new approach to model this oscillatory behavior as well as a frequency analysis is shown. This plant structure poses difficulties for control, as there is a substantial delay time in the plant and the disturbing oscillations depend on the quantitatively unknown internal feedback. To cope with these problems, a new control structure is proposed. Further a prediction based approach is presented, which allows to eliminate the periodic patterns in the oscillations and thus to lead those to rest.**

Index Terms – Quasi periodic disturbance, delay system, disturbance suppression.

I. The Continuous Casting Process

The main setup of a continuous casting plant, also described e.g. in [1], [2], [3], [4], and [5], is shown in Fig. 1. Liquid steel is transported through the ladle to the tundish, basically a liquid steel reservoir, where the level is kept constant. The level control therefore is not problematic and in this work not of our concern.

From the tundish liquid steel flows through a nozzle and a pipe (usually a submerged entry nozzle) to the water cooled mold, where solidification starts. Supported through rolls and under constant cooling and thereby solidification the strand is transported downwards. At the horizontal end of the plant the strand is fully solidified and can be cut into slabs without interruption of the continuous process.

Usually, i.e. for large slab formats, the casting speed (velocity of the strand) is given and only the inflow of the mold can be regulated through some hydraulic activated valve (e.g. stopper - nozzle system or sliding gate system). The level of the liquid steel in the mold is needed as control input and is either measured with a radioactive or an electromagnetic method.

The plant to be controlled has a simple structure as shown in Fig. 2. The servo system, which is fast compared to the rest of the plant, sets the flow through the pipe. The liquid steel flow through the pipe is modeled as simple time delay and represents a fall time.

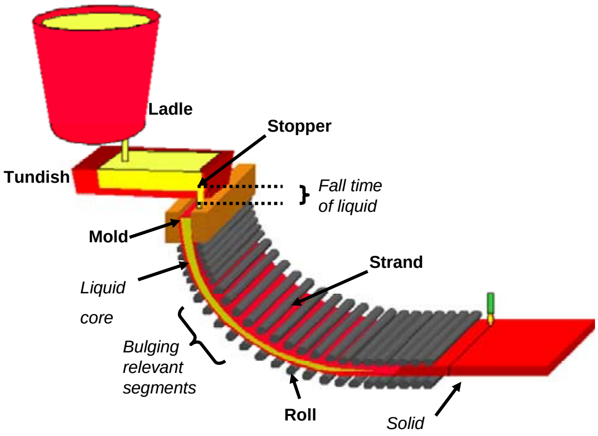

Fig. 1: Continuous Casting Scheme

The mold itself is a simple reservoir and can be modeled as integrator. Its outflow is a simple subtraction at the input of the integrator and is given by the casting speed multiplied by the surface of the mold A. The measurement of the mold level is denoted by the sensor block and due to difficulties in measuring in this harsh environment, is one of the biggest obstacles for fast level control.

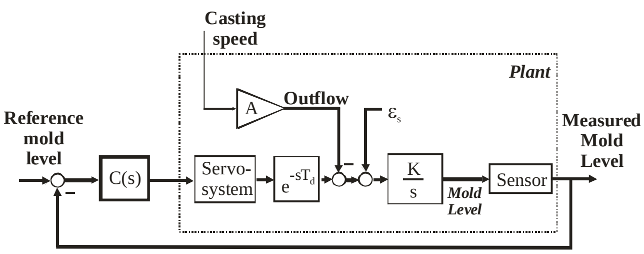

Fig. 2: Scheme of basic plant and simple feedback control

Many disturbances, such as surface waves in the mold, applied oscillation of the valve servo system (dither) and voluntary oscillation of the mold, act on the system. Additional difficulties ([6]) are caused by increased and reduced steel flow due to clogging and unclogging effects in the valve and the pipe. The measurement of the actual level is also very difficult, since e.g. for radioactive sensors an inherent averaging time of about 1 second is necessary and despite this averaging, the signal is still heavily disturbed.

Because of these disturbances, uncertainties, time delays and the slow sensor the standard feedback loop, also shown in Fig. 2 and denoted as $C(s)$, needs to have a low bandwidth.

However in certain plants periodic disturbances, in Fig. 2 denoted as ε_s, act on the inflow to the mold, which come from dynamic bulging ([7] [8]), a process to be described later in more detail.

These periodic disturbances, especially their higher harmonics cannot be rejected with the slow standard feedback controller, because of its band limitation, as mentioned above. Even worse, the internal feedback keeps the oscillations upright and the mold level can increase beyond the acceptable limits. This can lead, if the process is not stopped instantly, to outflow of the mold or even to a burst of the strand shell and to costly plant downtime.

II. The Process Of Dynamic Bulging

Since dynamic bulging causes periodic disturbances, which are hard to suppress using current control methods as given for example in [9] [10] [11] [12] [13], this process is described in more detail and later on a qualitative model therefore is derived.

The strand solidifies from outside to inside downward the strand. Due to increasing pressure inside the strand bulging occurs between rolls, as shown in Fig. 3. Usually a few meters downward the strand, the bulges are at their maximum, since the gravity driven pressure inside the strand is already high and the shell thickness is still low. Additional cooling can sometimes reduce bulging, since the shell solidifies earlier. Also reducing the roll distance in the design layout and lowering the casting velocity usually reduces bulging.

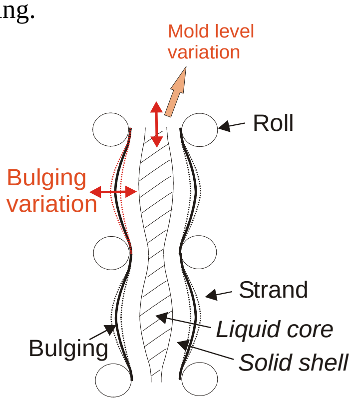

Fig. 3: Dynamic Bulging

As long as the steel structure of the shell is not changing and the casting velocity is kept constant, bulging is constant as well. The bulges of the strand simply act as additional seepage reservoirs.

Various causes constantly create disturbances in the shell of the strand. These lead to degradation of the steel structure and in general increase the bulging behavior of the plant. As long as the implanted disturbances are random, the ductility, even so degraded, is constant and with that bulging, at least for constant casting velocities, is constant as well. Also mold level fluctuations cause degradation of the solidified steel shell and even lead to modulations of the shell thickness, but do not necessarily cause problems in normal operation, as long as the fluctuations are uncorrelated, as mentioned above.

If mold level fluctuations, especially due to the feedback control, are not random, they can lead to a strongly varying shell structure and shell thickness and with that to a varying bulging magnitude between rolls. In Fig. 3 these variations around the normal bulging line (solid) are drawn as dotted lines. This behavior is called dynamic bulging and leads to a varying reservoir for liquid steel inside the strand between two consecutive rolls. It has to be mentioned that this effect takes place between several roll gaps and therefore the varying reservoir of the entire strand might not change significantly due to averaging. However if the disturbance pattern on the strand shell is varying with the period length of about the roll distance, then the varying reservoirs between rolls sum up and the overall reservoir of the strand varies strongly.

Since the strand is closed on one side due to solidification, liquid steel can move only from and to the mold. This however results in additional mold level flow from and to the strand besides to the standard inflow through the nozzle. These additional fluctuations cause in turn varying shell structures and shell thicknesses.

Thus mold level variations are the main reason for generating patterns of steel structures of the shell as well as shell thickness modulations which provoke dynamic bulging. This leads further through some internal feedback, given through the strand, again to mold level variations. If the controller is not capable of suppressing those variations, this can lead to self-exciting variations, which are due to nearly constant roll spacing in many plants, approximately periodic and increasing. This can lead to severe mold level oscillations, a fact usually called mold level hunting (MLH). In many plants together with certain steel grades, MLH would become unbounded and the casting process has to be stopped before it would lead to a burst of the shell and to a flow out of liquid steel. In some plants MLH does not go unbounded and never exits some maximum, but still degrades the quality of the final product severely.

Hence a good controller should be able to compensate for MLH and keep the mold level constant. MLH should decay and should never be excited again. Problems in compensating for MLH arise due to large time delays in the actuator, i.e. the fall time of the liquid steel in the submerged entry nozzle (SEN) and because of the difficulties in measuring the mold level.

III. The Dynamic Bulging Model

For better understanding of the bulging process a model is derived, which can be further used in simulations to test controller candidates. It can be easily implemented and tuned to reflect the basic behavior of a given plant. Furthermore it is attempted to keep the model linear to allow simple frequency analyses of the control loop.

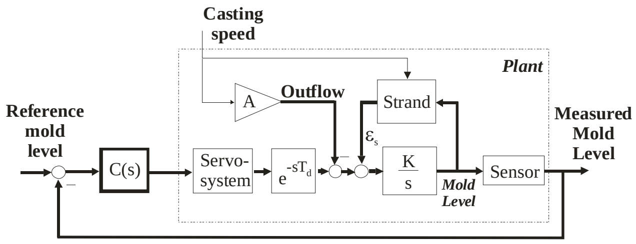

Fig. 4: Internal Feedback

The bulging model acts as an internal feedback of the plant. The derivative of the mold level serves as input to the bulging model and the resulting output of it is added to the inflow of the mold. The configuration is shown in Fig. 4, where the internal feedback is denoted as Strand. It is also shown and described later, that the casting speed is also an input to the bulging model.

For simplicity, it is assumed in following derivations that the strand is traveling with constant velocity. Therefore the spatial space properties can be directly mapped into time.

For the development of the bulging model following basic transfer functions, here listed for convenience, are used:

$$G_{Td}\left(s\right) = e^{-sT} \tag{1.1}$$

$$G_{MA}\left(s\right) = \frac{1-e^{-sT}}{sT} \tag{1.2}$$

$G_{Td}\left(s\right)$ is simply a time delay and $G_{MA}\left(s\right)$ is a moving average filter with averaging time T.

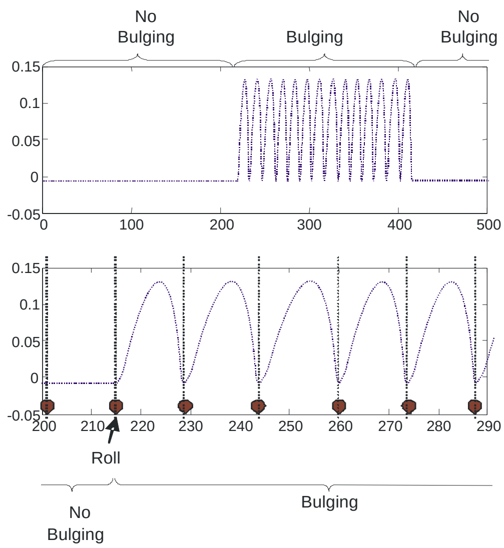

Fig. 5: Bulging generation

Using (1.1) and (1.2) to build up the behavior of one roll spacing we get for the given setup (1.3) and (1.4) respectively:

$$G_{i\,Td}\left(s,T_i\right) = e^{-sT_{vi}} \tag{1.3}$$

$$G_{i\,MA}\left(s,T_i\right) = \frac{1-e^{-sT_i}}{sT_i} \tag{1.4}$$

T_{vi} is the traveling time the strand needs from the meniscus (surface) in the mold to the roll gap i and T_i is the time needed via the corresponding roll gap.

Additionally bending curves are assumed to weight the effects of the disturbances in the roll gaps i and are described as transfer functions $G_{Bi}\left(s,T_i\right)$. All bending curves of the individual roll gaps can be assumed to be equal for simplicity and only differ in the spatial length and respectively in time domain by T_i, hence $G_{Bi}\left(s,T_i\right) = G_B\left(s,T_i\right)$ can be implemented.

Using the bending curve $G_B\left(s,T_i\right)$, the moving average filter (1.4) and the time delay (1.3), we get the transfer function for one roll gap as:

$$G_i\left(s,T_i\right) = G_B\left(s,T_i\right)\frac{1-e^{-sT_i}}{sT_i}e^{-sT_{vi}} \tag{1.5}$$

Summing up the effects of all roll gaps and weighting those by some factor g_i we get

$$G\left(s\right) = \sum_i g_i\, G_i\left(s,T_i\right) \tag{1.6}$$

where the time to each roll gap is given by:

$$T_{vi} = T_m + \sum_{l=1}^{i-1} T_l \tag{1.7}$$

T_m denotes the traveling time of the strand from the mold level to the center of the first roll. Since there exists very little bulging between the first rolls and between the final rolls in the strand we can set associated weighting coefficients g_i equal to zero. A graphical interpretation can be seen in Fig. 5. From a practical point of view there usually exists a bulging dominant segment, which consists of about 10 to 15 consecutive rolls around the bender. The distance to this segment as well as the amount of influencing roll gaps can be estimated either by physical plant knowledge or data analysis.

The delay times T_i are constants for a constant casting speed. There is however a clear connection between T_i and the casting velocity by the constant, spatially given roll distances d_i:

$$T_i\left(v(t)\right) = \frac{d_i}{v(t)} \tag{1.8}$$

IV. The Additional Control Input

Using data based techniques, i.e. correlation methods, on many measurement channels of the casting process, additional channels were identified to give supplementary information of the plant to be controlled.

In [14] it was found that the moments of some roll motors correlate with the almost periodic disturbance. Additionally it could be shown, that especially the moments of the roll motors in the bulging critical segments (about 3 m downward the strand) correlate with the disturbance and are in phase to each other. Further could be shown, that averaging these moment signals gives a very good estimate of the disturbance signal in the MLH relevant frequency bandwidth.

In general the average moment of the rolls is varying due to friction and weight of the strand over a large magnitude range. Fortunately it varies only in a low frequency range below the bulging frequencies, and high-pass filtering can extract the desired disturbance signal well. Of advantage is a linear phase filter since the introduced phase shift can be treated as simple time delay in the following controller design.

The filtered averaged moment signal $\varepsilon_M(t)$, shown in Fig. 6, is approximately $k_1.\varepsilon_s(t-T_{d2})$, where T_{d2} is given through the filter. The factor k_1 is unknown and has to be determined trough identification in advance.

V. The Controller

The controller is divided into two separate controllers as shown in Fig. 6. The first is the standard feedback controller $C(s)$ using the measured mold level and its bandwidth is set below the bulging frequencies. The second controller is using the filtered averaged moment to explicitly compensate for MLH. The idea of using the moment signal of the roll motors to compensate for MLH was first presented and patented in [14].

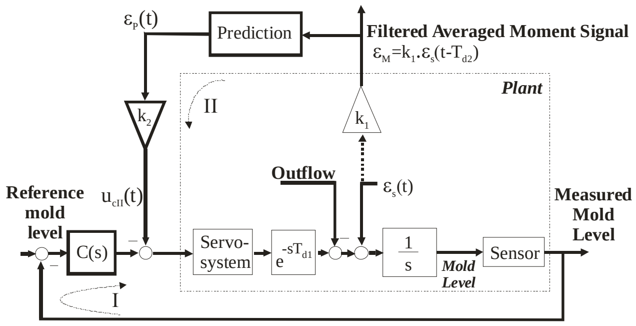

Fig. 6: New control scheme

Since the servo system is fast, its dynamics are ignored and for simplicity it is assumed as constant gain equal to 1. It should be noted, that if the model of the servo system is known, an approximated inverse of it could be used in the controller.

The second controller is chosen simply as ahead predictor of the delay times and a simple gain. The predictor is used to predict for the delay time in the plant T_{d1} and the introduced delay time T_{d2} due to the roll moment signal filtering. Therefore the gain k_2 only has to be chosen to be $k_2 = 1/k_1$ to compensate for the disturbance. This means that ideally

$$\varepsilon_P(t) = k_1\,\varepsilon_S(t+T_{d1}) \tag{1.9}$$

and

$$u_{cII}(t) = k_1\,k_2\,\varepsilon_P(t) = \varepsilon_S(t+T_{d1}) \tag{1.10}$$

will hold.

If $\varepsilon_S(t)$ is assumed to be periodic the prediction $\varepsilon_P(t)$ can be calculated as

$$\varepsilon_P(t) = \varepsilon_M\left(t-\tau^* + T_{d1} + T_{d2}\right), \tag{1.11}$$

where τ^* is the period length of the fundamental of $\varepsilon_S(t)$. Note that τ^* is approximately constant for a given, constant casting speed.

Since the period length τ^* is only known approximately, it is calculated in each step through minimization of the quadratic cost function

$$J(\tau) = \frac{1}{2}\int_{t-T_{\max}}^{t} \left(\varepsilon_M(\xi) - \varepsilon_M(\xi-\tau)\right)^2 d\xi, \tag{1.12}$$

where $T_{\max} > \tau^*$. The cost function is periodic and has local minima at multiples of τ^*. Therefore the initial condition τ_0 must lie within the concave region containing τ^*. To solve for τ^*, a simple gradient minimization procedure, as in [15], can be used. Practically τ_0 can be chosen close to τ^* and for slightly varying τ^* a simple PLL (phase locked loop) algorithm can be used successfully.

Above it was assumed that the filtered averaged moment signal is periodic. However this is only an approximation and if the casting speed is changed or MLH is already almost eliminated due to the control, the disturbance signal looses its periodicity. No clear minimum of the quadratic cost function can be found and therefore the prediction has to be turned off and instead of the predicted signal the measured signal directly ($\varepsilon_P(t) = \varepsilon_M(t)$) has to be used. This means that for the dead time cannot be compensated for, which is again no problem, since the bulging is not periodic in this case.

In the following section the data analyses is shown. It shows the effectiveness of this approach.

VI. Data Analysis, Results

Following data analysis is carried out with one measurement data set, in which different casting velocities occur. The data is sampled with 5 Hz and all FFTs are calculated over 512 samples. In the spectrum plots red stands for high magnitudes, yellow for medium magnitudes and dark blue for low magnitudes.

In Fig. 7 the casting velocity of the data set is plotted and in Fig. 9 the associated spectrum of the mold level inflow (differentiated mold level signal) is shown. The frequencies due to dynamic bulging can be clearly seen as horizontal lines with higher magnitude and are marked with numbers denoting the fundamental wave (1.) and the higher harmonics (2., 3., etc.). It can be also clearly seen that MLH increases in the time span from 3000s to 4500s.

In Fig. 8 an excerpt of the spectrum shown in Fig. 9 is taken around t=4000 s to clearly show these harmonics.

By feeding back the measured averaged moment signal and using an ideal in advance determined k_2, the spectrum as shown in Fig. 10 is generated. This corresponds to the controller shown in Fig. 6 without the ahead prediction. It can be seen in the spectrum, that for the first and the second harmonics an enhancement can be achieved (the horizontal lines almost disappear), but the higher harmonics cannot be removed.

Using the controller shown in Fig. 6 with the ahead prediction, the spectrum as shown in Fig. 11 can be achieved. Clearly the periodic pattern is destroyed and MLH would disappear. In Fig. 12 the predicted period length (in samples) is shown. When the prediction does not find a clear minimum for the period length, the predictor is turned off and the value is set to zero. It can be seen, that despite the disturbance signal is not absolute periodic, it is still possible to compensate the disturbance most of the time by ahead prediction.

Using the approach with the prediction, mold level hunting can be eliminated. This can be seen in Fig. 13, where the MLH compensation was turned on at t=1500s.

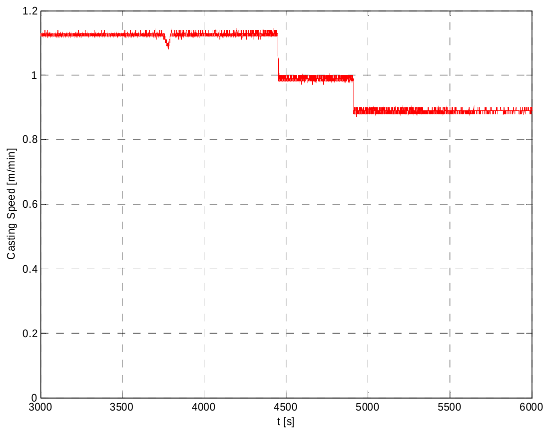

Fig. 7: Casting Speed

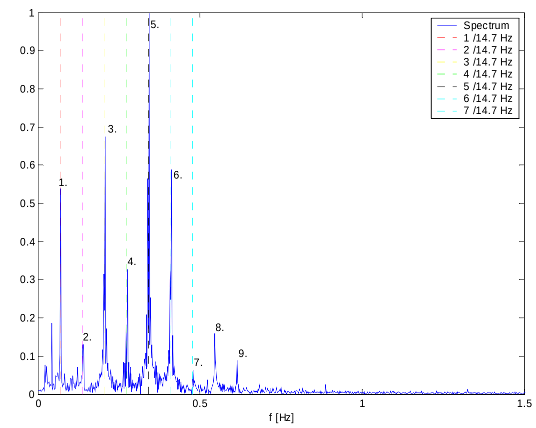

Fig. 8: FFT of MLH at t = 4000 s

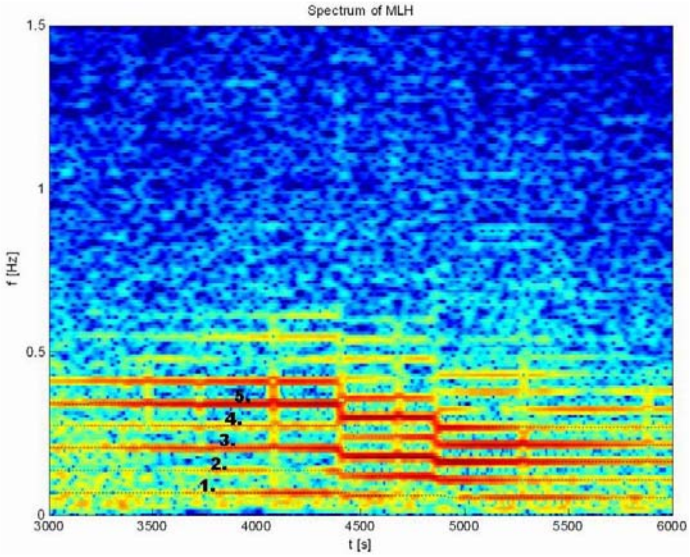

Fig. 9: Spectrum of MLH

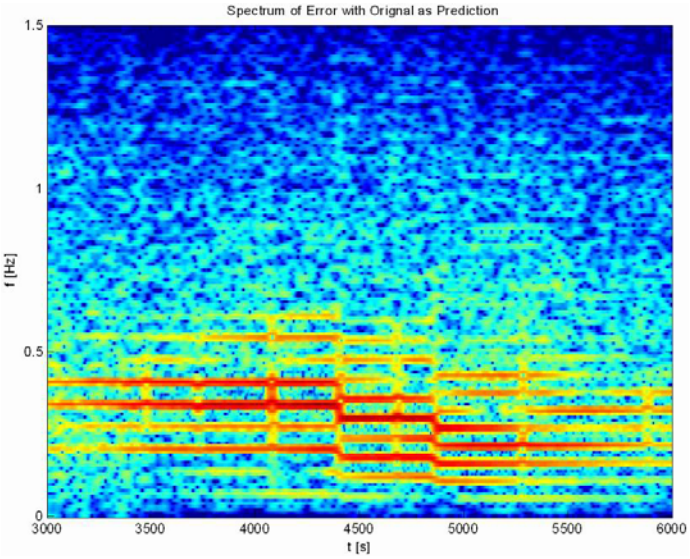

Fig. 10: With Feedback of Moment Signal

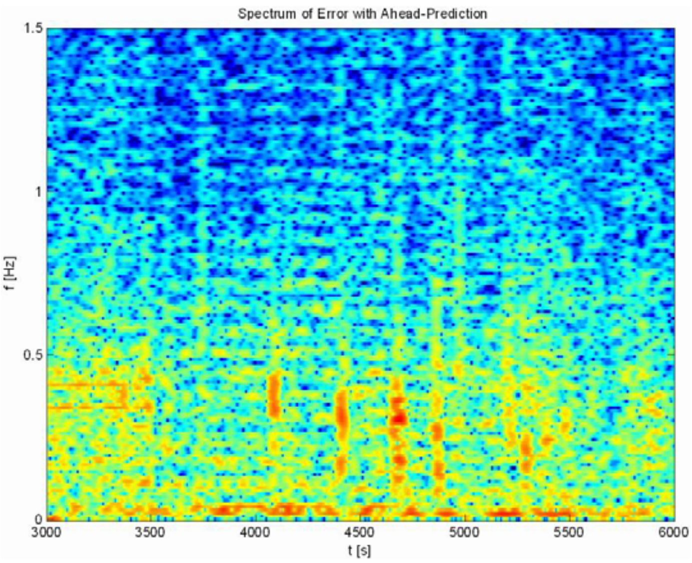

Fig. 11: With Feedback of Predicted Moment Signal

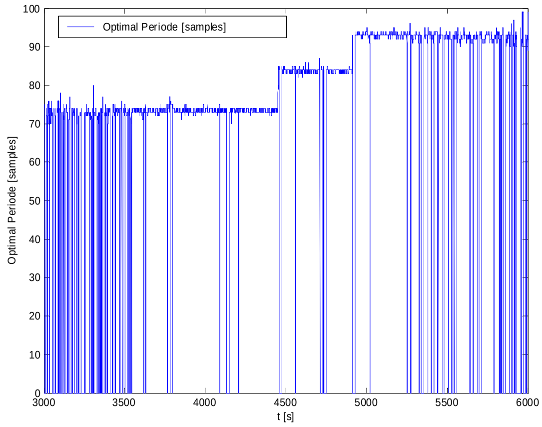

Fig. 12: Predicted Period Time (in Samples, Ts=0.2 s)

Since the disturbance is only approximately periodic the error does not become zero, the periodic components however are destroyed and therefore MLH does not occur again. Fig. 14 shows in more detail the time slot, where the compensator was switched on.

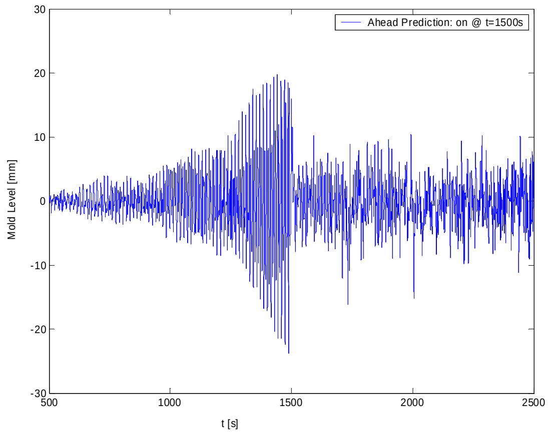

Fig. 13: Mold Level (Prediction turned on at t=1500 s)

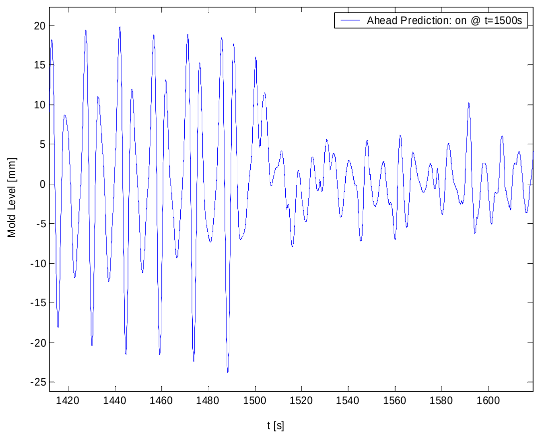

Fig. 14: Mold Level (Zoomed in)

VII. Conclutions

In this paper a model of the dynamic bulging process and a controller to eliminate mold level hunting have been presented. For the controller, an additional control input, the averaged roll moment, has been used. This signal is a good estimate of the disturbance due to dynamic bulging and because of its periodic behavior it has been possible to predict this signal ahead. This prediction has then been used to compensate dynamic bulging, despite delay times within the plant.

In this work the delay time in the plant and plant gains have to be determined beforehand. To avoid this, an adaptive scheme is currently in development, to adaptively tune the feedback gain and the ahead- prediction time.

VIII. Acknowledgment

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