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Control issues in continuous casting of steel

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Abstract: Continuous casting plants are highly complex plants whose performance requires reliable mold level control system. Several effects greatly influence the surface quality of the final product and if these are not suppressed sufficiently by the mold level control system, than the production speed, hence the productivity has to be lowered. This paper analyses the most important disturbance and their effects on the control system design, and presents a new solution for the most critical case, mold level hunting.

1. INTRODUCTION

In the last few years the world steel production has rapidly increased from 848 million metric tons in 2000 to 1219 million metric tons in 2006 (IISI). Since more than 90 % of the total steel production is solidified using continuous casting, enormous efforts have been made to increase throughput and quality of the final product. This requires improved control systems, in particular the mold level control system. Therefore various methods have been developed (Barrón *et al.*, 1998, Blanchini *et al.*, 2000, de Keyser, 1997, Dussud *et al.*, 1998, Graebe *et al.*, 1995, Hesketh *et al.*, 1993, Kitada *et al.,* 1998) in the last decades. However there are still many difficulties since there is a large input delay of the system while large disturbances can occur. In particular at higher production speeds or for special steel grades (peritectic steel) a disturbance can start almost periodic disturbances which can become dominant leading to instabilities, which is then usually called mold level hunting (MLH) and which can produce very serious damages.

In this paper we present an overview of the most important disturbances and uncertainties affecting the mold level control system, in particular of the disturbance leading to dynamic bulging. Basic requirements for the control system are highlighted and a new control strategy is presented.

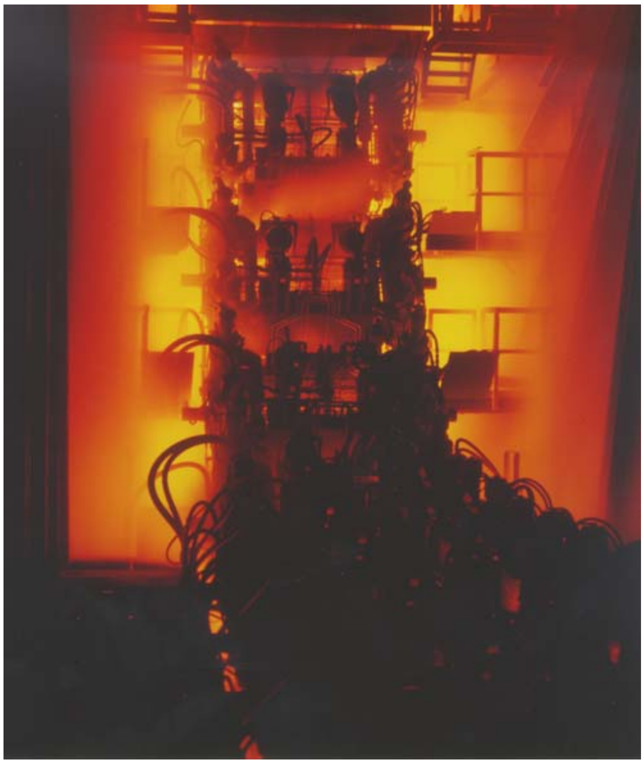

Fig. 1. Continuous casting plant, Krakatau, Indonesia [Courtesy of Siemens AG]

2. THE CONTINUOUS CASTING PROCESS

Fig. 1 shows an industrial continuous cast plant to produce steel slabs and Fig. 2 its scheme. Molten steel is transported with the aid of a crane in a large vessel, commonly referred to as a ‘ladle’, to the continuous casting plant. The molten steel is then poured into the ‘tundish’, basically a liquid steel reservoir of molten steel for continuous operation.

From the tundish, liquid steel flows through a valve (usually a stopper servo system or a sliding gate system) and a pipe (usually a submerged entry nozzle, SEN) to the water cooled mold, where the solidification process starts. At the walls of the cooled mold, solidified metal forms a semi rigid shell creating a steel container with a liquid steel core, exiting the mold at its bottom. Clearly, a smooth surface of the newly formed shell is important since any unwanted ruptures could spill liquid steel. Supported by rolls and under constant cooling, and thereby solidification, the generated steel ‘strand’ is transported downwards, where it can be cut into slabs and be removed from the plant without any interruption of the continuous process. In principle there are two possibilities to keep the level of liquid steel in the mold constant, either to regulate the casting speed and keep the inflow to the mold constant or to regulate the inflow to the mold and keep the casting speed constant. The first method puts much stress on the mechanics and can only be used for small formats. The second method is more common and will be considered throughout this work.

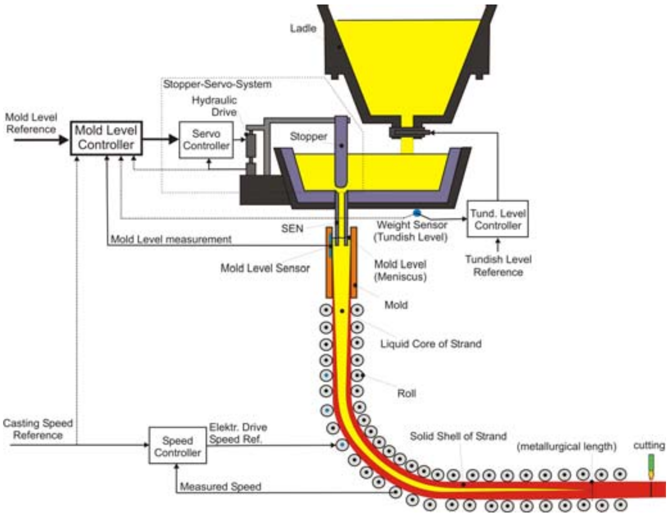

Fig. 2. Scheme of continuous casting plant

Fig. 2 shows also the major control systems in continuous casting. The speed controller usually works on individual roll drives downward the strand and generally keeps the velocity of the strand constant. In modern plants this control rarely causes problems since powerful and robust drive motors are utilized. Also the tundish level controller is indicated in the figure. The level height of the tundish depends on process variations, such as ladle changes and so level variations have to be tolerated. This control system is also uncritical and simple controls (e.g. PI control) are sufficient, hence it will not be discussed further in this work.

The mold level control is more critical. The liquid level in the mold should be as flat as possible to provide a smooth shell formation. Unfortunately the process of continuous casting invites many uncertainties and disturbances such as the clogging and unclogging of the SEN (Rackers *et al.,* 1995), unwanted surface waves (Boisdequin *et al.*, 1997), uncertain sensor dynamics (Boisdequin *et al.*, 1997) and uncertain actuator dynamics (Graebe *et al.*, 1995, Radot *et al.*, 2003).

3. MODELLING

3.1 Basic Plant Model

Fig. 3 shows a very simple model for the mold level control process. The inflow is regulated through the control input to a hydraulic activated valve (actuator) and the flow through the pipe can be modeled as simple gain g_u and a time delay τ. The time delay combines the fall time of the liquid steel in the SEN and other delays of the stopper servo system. The mold itself is a simple reservoir and can be modeled as an integrator. The outflow of the mold Q_{out} is the casting speed multiplied by the surface A of the mold. The measurement of the mold level is either performed with a radioactive or an electromagnetic method. Radioactive sensors can usually be modeled as moving average filters and electromagnetic sensors as first order low pass filters.

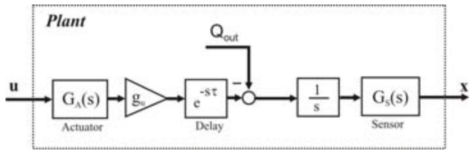

Fig. 3. Simple plant model

3.2 Disturbances

While figure 3 correctly reproduces the main function, the reality looks more complex, as several uncertainties and disturbances occur, as shown summarily in Fig. 4.

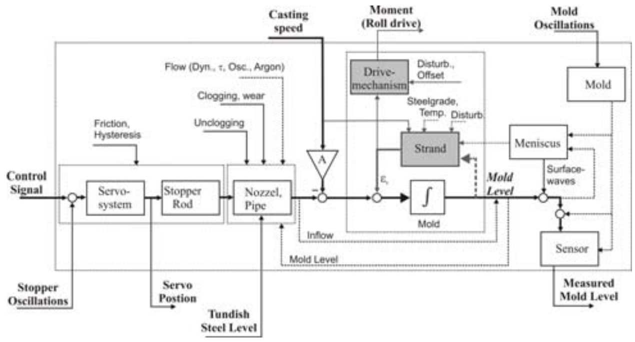

Fig. 4. Plant model with disturbances

In modern plants the stopper servo systems work accurately and fast, friction and hysteresis are usually negligible. Thus, in most cases stoppers can be modeled as linear first order systems. However, modeling the valve and the SEN only with a gain g_u and a time delay τ is possible only if g_u is allowed to change suddenly due to clogging and especially unclogging, unpredictable effects mostly observed only indirectly, for instance through a reduced flow or argon gas back pressure. The gain g_u changes further also according to the mold level height. This dependency can be compensated by measuring the mold level height. Other nonlinearities of the valve, in particular for sliding gate systems, are known and can be compensated. As already mentioned, the mold can be modeled as integrator and the outflow Q_{out} is known due to the given cross section of the mold and the accurately measured casting speed. Only the actual position of the stopper is often not precisely known (in particular after a stopper change), which can be modeled as an unknown constant offset of the inflow.

Several other disturbances indicated in Fig. 4 are also important for the controller design, their frequency ranges for a typical large slab caster in Fig. 5 (top). For example small random disturbances are given in the measurement of the mold level through sensor noise. But also real fluctuations of the mold level occur. In most plants argon gas is injected through small openings into the SEN or at the tip of the stopper to avoid air aspiration and clogging, this however leads to a random disturbance of the mold level in a frequency range of 0.1 – 0.7 Hz as shown in Fig. 5 (top). Other disturbances of the mold level are recirculation effects in the mold, given by dynamically changing flow patterns of the liquid jet flow inside the mold (Boisdequin *et al.*, 1997). These disturbances depend much on the geometry of the SEN and in particular its nozzle openings and are typically in a frequency range of approximately 0.05 – 0.3 Hz.

Further a periodic disturbance can arise due to unbalanced rolls in the strand. The frequency of this disturbance (and possibly of its second harmonic) is rather low and obviously depends on the casting speed and the diameter of the roll. At some plants also the stopper is voluntarily oscillated with a frequency usually around 5 Hz to avoid clogging. Moreover, on most plants also the mold itself is oscillating for metallurgical reasons in the order of 1.5 – 3 Hz, on one hand to avoid sticking of the freshly formed strand shell and on the other hand for improved shell formation.

Other large disturbances are given through surface waves (gravity waves). Surface gravity waves can be excited through various disturbances or by the controlled inflow. Typically about 5 to 6 modes can be present and their frequency f_{gw} can be estimated as

$$f_{gw} = \frac{1}{2\pi}\sqrt{\frac{m\pi g}{l_1}}, \quad m = 0,1,..6 \qquad (1)$$

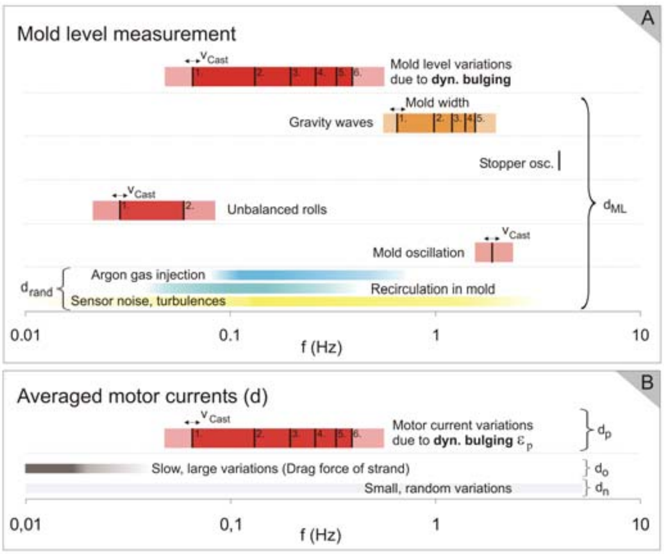

Fig. 5. Frequency ranges of disturbances

The variable m is the mode, g the gravitational constant and l_1 the width of the wide side of the mold (Furtmueller *et al.*, 2007). Surface gravity waves cannot be actively compensated by the control system since this acts only on the whole tundish and the average mold surface is constant, only the shape of the liquid surface varies. It is however important that the control system does not further excite those waves.

The most critical disturbance is dynamic bulging, a periodic disturbance (ε_s ,Fig. 4) with harmonics typically up to the 6th order. The disturbance is generated through a feedback inside the plant indicated by the gray block 'Strand' in Fig. 4.

As mentioned before, the strand solidifies by initially forming a solid skin that solidifies toward the liquid center core of the slab as the strand moves downward the plant. Due to an increasing pressure inside the strand, the opposing solidified surfaces of the shell bend outwards as it passes between two consecutive rolls. This deflection is commonly called bulging. Further down the strand, the bulges reach their maximum since gravity driven ferrostatic pressure inside the strand is already high and the shell thickness is still low. As long as the steel structure of the strand shell does not change and the casting velocity is kept constant, bulging is constant as well. Since the strand thickness at each bulge increases the space for containing the liquid steel inside the strand, they simply act as additional reservoirs for the molten steel. However, distortions and defects of the freshly formed shell of the strand are constantly generated by various sources. These sources lead to a degradation of the steel structure and an increase of the bulging behavior of the strand. As long as the implanted disturbances are random, the diminished ductility and bulging is constant for continuous casting velocities. If mold level fluctuations are not random, as a result of insufficient feedback control, they can lead to a strongly varying shell structure and thickness, and thereby lead to a varying bulging magnitude between rolls. This behavior is called 'dynamic bulging' and leads to a varying reservoir for liquid steel within the strand. This effect takes place between numerous roll pitches and therefore the effective averaging of the varying reservoir of the entire strand might not change significantly. However, if the disturbance pattern of the strand shell is varying with the spatial period length equal to the roll distance (roll pitch), then the varying reservoirs between rolls sum up and the overall reservoir of the strand can vary strongly.

Since the strand solidifies by forming an external shell, the contained liquid steel tends to propagate between the mold and the strand. Note that the strand is closed on one side due to solidification. This, however, results in an additional flow besides the regulated inflow through the nozzle and the 'outflow' given through the (usually constant) casting speed. This additional flow inside the strand leads to additional mold level variations causing, in turn, a varying shell structure and shell thickness if not compensated sufficiently by the inflow through the SEN. 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 (Lee *et al.*, 2000). Dynamic bulging again causes mold level variations through the liquid backflow (internal feedback) given by the strand. Hence if the controller is not capable to suppress these mold level variations, these variations will be approximately periodic and increasing (mold level hunting, MLH).

A model of the dynamic bulging process has been developed in (Furtmueller, 2007). It shows that changes of the mold level are the main cause of disturbances in the strand shell.

Therefore the transfer function $G_{S1}(s)$, basically a derivative, can be used to generate the varying strand shell structure out of the mold level, which in its turn can be weighted in the bulging dominant segments with $G_{S2}(s)$ to generate additional inflow and outflow of the mold. For simplicity, it is assumed in the following derivations that the strand is traveling with constant velocity. Therefore the spatial space properties can be directly mapped into the time. Here T_{vi} is the traveling time which the strand needs to travel from the meniscus (surface) in the mold to the roll pitch i and T_i is the traveling time the strand needs to travel via the corresponding roll pitch. Bending curves weigh the effects of the disturbances in the roll pitches i and are described as transfer function $G_{Bi}(s,T_i)$. For simplicity all bending curves of the individual roll pitches can be assumed to be equal and only to differ in the spatial length and in time domain by T_i, hence $G_{Bi}(s,T_i) = G_B(s,T_i)$.

Using the bending curve $G_B(s,T_i)$ the transfer function for one roll pitch can be assumed to be:

$$G_i(s,T_i) = G_B(s,T_i)\frac{1-e^{-sT_i}}{sT_i}e^{-sT_{vi}}. \tag{2}$$

Summing up the effects of all roll pitches and weighting them by some factor h_{Bi} we get

$$G_{S2}(s) = \sum_i h_{Bi}\, G_i(s,T_i) \tag{3}$$

where the time to each roll pitch is given by:

$$T_{vi} = T_0 + \sum_{l=1}^{i-1} T_l. \tag{4}$$

Here T_0 is the traveling time of the strand from the mold level to the center of the first roll. There is very little bulging between the first and between the last rolls in the strand, so the associated weighting coefficients h_{Bi} can be set to zero. In practice, there usually exists a dominant bulging segment of about 10 to 15 consecutive rolls around the bender. The distance to this segment as well as the amount of influencing roll pitches can be estimated either by physical plant knowledge or data analysis. The time delays T_i are constants for a constant casting speed and there is a clear connection between T_i and the casting velocity by the constant spatially defined roll distances l_i, given by $T_i(v(t)) = l_i/v_{cast}(t)$.

The entire feedback $G_{Strand}(s)$ is simply the system, which generates the disturbance at the shell and the summation of the disturbance of the entire strand:

$$G_{Strand}(s) = G_{S2}(s)G_{S1}(s). \tag{5}$$

The overall feedback path, described by (5) can be seen as a filter which suppresses all frequencies except the dynamic bulging frequencies shown in Fig. 5.

3.3 Extended Plant Model

Recent findings (Furtmueller *et al.*, 2007) showed that an additional measurement is available to estimate the disturbance due to dynamic bulging. In particular the motor currents of the roll drives can be measured, hence also be used in the control. In Fig. 6 this additional output is denoted as d and can be assumed as

$$d(t) = \underbrace{g_d\ \varepsilon_s(t)}_{d_p(t)} + d_0 + d_n(t). \tag{6}$$

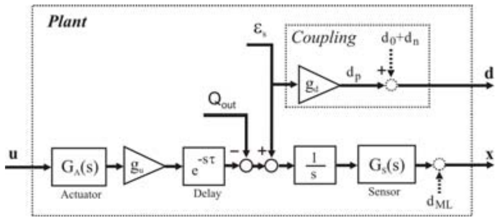

Fig. 6. Extended plant model

The measurement d is also indicated in Fig. 5 (bottom) and can be used to estimate the almost periodic disturbance ε_s, d_0 is a slowly varying offset, and d_n is a small noise essentially uncorrelated with the mold level measurement. The periodic oscillations due to dynamic bulging change only slowly due to the special structure of the strand feedback so the disturbance can be treated as generated by an exosystem.

3. CONTROL SYSTEM

In most industrial plants PID control is used, as it can be tuned directly at the plant during commissioning. In this section an optimal tuned PID control strategy is presented, which shows the limits of feedback control in case of dynamic bulging.

For the controller design and for the following analysis we use the simple the plant model shown in Fig. 3. The actuator and the sensors have been assumed as first order low pass filters with time constants of 0.1 and 0.12 respectively. For the time delay $\tau = 0.5\,s$ has been assumed. The PID controller has the form

$$C(s) = \frac{1}{g_u}k_c\left(1 + \frac{1}{T_i}s + T_v\frac{s}{0.1s+1}\right) \tag{7}$$

with the parameters $k_c = 0.82$, $T_i = 22$ and $T_v = 0.24$. Here a phase reserve of 60° was desired in the controller design for the assumed maximum time delay of $\tau = 0.5\,s$ and an input gain g_u, subject to a maximum uncertainty of $\pm 10\%$. The integral action has been added to guarantee zero steady state error, despite an unknown inflow offset. This is important to keep a constant mold level if the casting speed is changed to another set point or in the case of clogging or stopper wear.

In the following the transfer functions that represent the open loop frequency response $L(s)$, the complementary sensitivity function $T(s)$ and the sensitivity function to dynamic bulging $D(s) = x(s)/\varepsilon_p(s)$ are used.

The PID coefficients have been fixed by minimization of $\max_{\omega=2\pi[f_{1B},f_{6B}]}|D(j\omega)|$ with $|D(j\omega)|\leq -10\,\text{dB}$ at $f=2.10^{-3}\,\text{Hz}$ and $|T(j\omega)|\leq -15\,\text{dB}$ for $f\geq 0.7\,\text{Hz}$. The requirement that $|D(j\omega)|$ is minimum between the first harmonic ($f_{1B}=0.07\,\text{Hz}$) and the sixth harmonic ($f_{6B}=0.42\,\text{Hz}$) of dynamic bulging is important for dynamic bulging suppression. If the plant is to be operated with different casting speeds can occur, the minimal possible bulging frequency should be chosen for f_{1B} and the maximal harmonic frequency for f_{6B}.

The requirement for $|D(j\omega)|$ at low frequencies is important for the suppression of disturbances due to casting speed changes, as mentioned before. The requirement $|T(j\omega)|\leq -15\,\text{dB}$ for $f\geq 0.7\,\text{Hz}$ has been chosen for smooth stopper movement and to avoid that gravity waves are excited. In Fig. 7 the Bode plots of $L(s)$, $T(s)$, $D(s)$ and the controller $C(s)$ are shown and the numerical numbers in the plot indicate the first six dynamic bulging harmonics. It can be seen that $D(s)$ becomes large at $0.5\,\text{Hz}$ and stays rather large at the dynamic bulging frequencies $[f_{1B},f_{6B}]$.

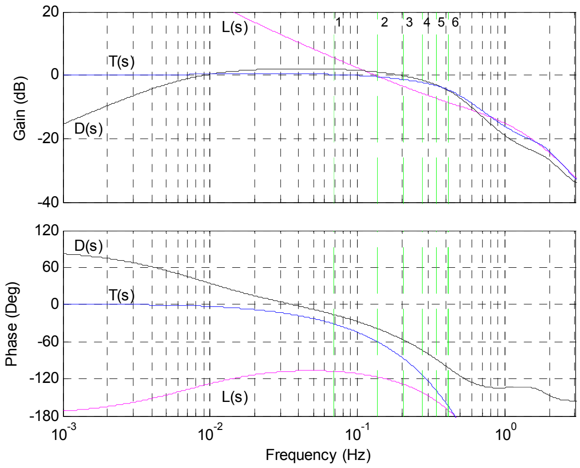

Fig. 7. Bode plots; basic plant

By using the parameterization of the optimal PID controller together with the plant given above and expanding the plant model with the 'internal feedback' given by the strand, we obtain the Bode plot of the loop gain $L(s)$ (see Fig. 8). The exogenous signal ε_s of Fig. 6 is here generated 'internally' in the plant by the model of the strand. Basically the same shape of $L(s)$ can be seen as in Fig. 7, with strong variations in loop and phase at the dynamic bulging frequencies. Exactly these variations can violate stability conditions, thus leading to MLH. Simply reducing the open loop gain $L(s)$ in an attempt to reduce dynamic bulging does not succeed, since the magnitude of $D(s)$, hence also the ripples in the Bode plot added through the additional dynamic bulging feedback will increase. This explains the limits of classic feedback control. This is also valid for advanced loop shaping techniques such as H_{inf} controller, since these again reduce $\max_{\omega=2\pi[f_{1B},f_{6B}]}|D(j\omega)|$ only slightly.

In general, the sensor and actuator dynamics are fast and the input time delay together with the unknown input gain are dominant for the plant model. By using a differential part, as done in a PID controller, the integral part of the plant is already inverted and basically only the time delay of the plant is left in the control loop. Hence higher order controller will only improve control by an inversion of the sensor and the actuator dynamics, leading to only minor improvements.

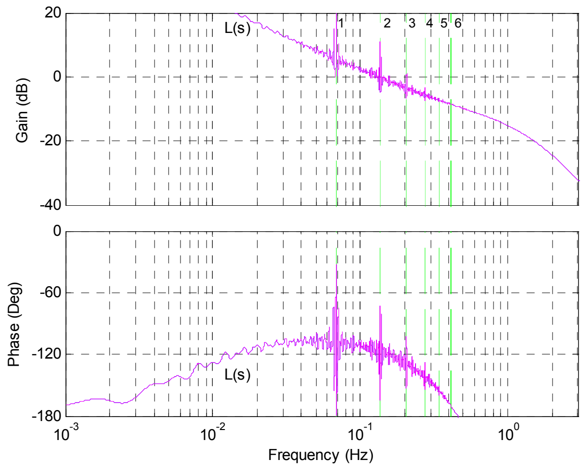

Fig. 8. $L(s)$ with strand feedback

Still, the (almost) periodic nature of the dynamic bulging can be exploited to avoid it by reducing the 'ripples' seen in the Bode plots without changing the standard feedback loop. This could be done by using the mold level signal itself to predict and compensate the periodic component of the disturbance, e.g. using internal model control. However, the mold level signal also contains other not predictable disturbances in the same frequency range as the disturbance due to dynamic bulging.

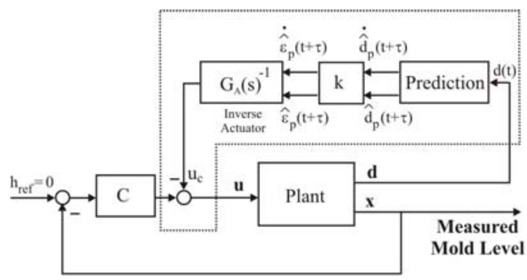

Fig. 9. Control with disturbance feed forward

A better possibility is to use the additional measurement d of Fig. 6 to directly estimate and predict the disturbance ε_s. This signal has also the advantage that in the relevant frequency range only little other disturbance is present (see Fig. 5). The disturbance compensation can then be done as indicated in Fig. 9 - for details see (Gruenbacher *et al.,* 2007).

Using the plant as described above with the control scheme of Fig. 9 the closed loop gain as shown in Fig. 10 is possible and mold level hunting will not appear anymore.

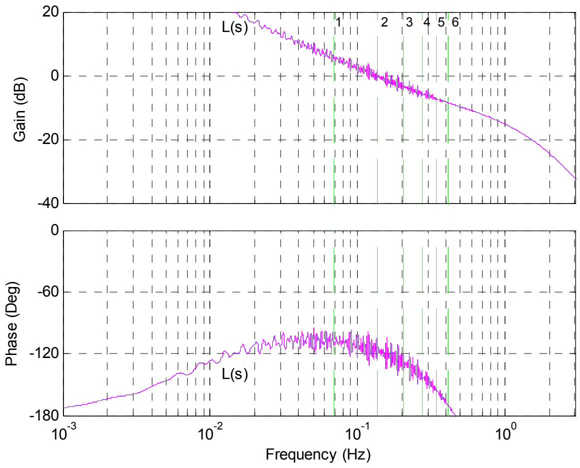

Fig. 10. $L(s)$ with active compensation

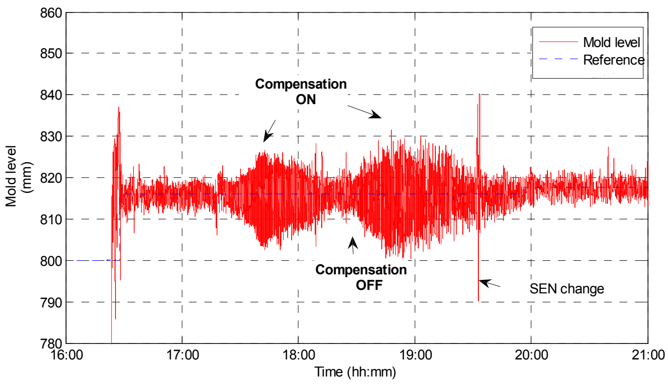

Fig. 11. Results at plant

3. RESULTS AND CONCLUSIONS

The control method presented has been applied at an industrial caster. It proved extremely successful as shown in Fig. 11. After dynamic bulging started appearing at approximately *17:35* the compensation was turned on at *17:45*. As a result, the mold level oscillations clearly decreased. After the compensation was turned off once again at *18:20*, dynamic bulging oscillations had increasing returned. Finally, when the compensation was turned on again at *18:50*, and kept on until the end of the trial, the mold oscillations reduced and then stayed within the accepted bounds. Note that the large mold level oscillations at time *19:28* was due to a SEN change and not dynamic bulging.

In summary, it can be said that existing mold level controllers tend to perform poorly or fail, since they are generally only pure feedback methods. Independently on the design method of the feedback the disturbances suppression capability is always limited due to the input delay of the plant, and pure feedback controllers have known limits in this respect. Because of this time delay full compensation is as a matter of principle only possible if a prediction is used. This fact has been considered in this paper and the 'almost' periodic nature of the dynamic bulging disturbance was utilized for prediction and compensation.

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