Institute for Design and Control
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Diploma thesis

Mold level control of a continuous casting plant by switching control strategies

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Abstract

In continuous casting plants especially at higher casting speeds dynamic bulging, a variation of the magnitude and/or the shape of the bulges, may occur and lead to a fluctuation of the height of molten steel with serious consequences in terms of quality and damage. A steady growth of these fluctuations is called mold level hunting. Presently both phenomena are met with a reduction of the casting speed.

This diploma thesis proposes a method based on switching control strategies, in particular the method of dynamic output feedback control and the average dwell time approach, to keep the process stable and to increase the throughput of such plants. Simulations with models of different complexity show a productivity increase of around 10 %.

Introduction

The demand for steel over the last decades has been increased and further increases are expected after the end of the actual crises also due to the development in countries like China and India. This increases the interest for a high (average) casting speed besides the usual economic considerations related to the plant.

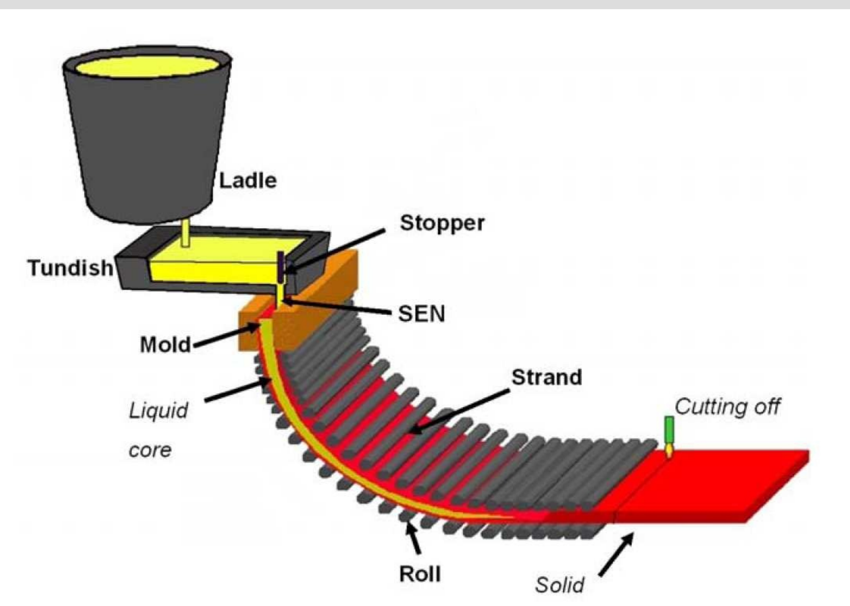
Especially for some steel grades and casting speeds above an given value the phenomena of dynamic bulging as well as mold level hunting can cause significant problems. Dynamic bulging stands for a change of the magnitude and/or the shape of the bulges of the strand and therefore for a fluctuation of the mold level, while mold level hunting is synonymous with a continuous growth of these fluctuations.

To ensure a good quality of the final product and to operate the plant safely at a high casting speed, the mold level has to be kept as constant as possible.

A large number of studies have been conducted in recent years. The developed methods differ both in the manipulated variables as well as the measurements used for control.

A completely different approach is presented here. The objectives will be achieved by linking modern results in switching control theory and in bulging detection. This can be done in two forms, either by using the method of dynamic output feedback control or by the average dwell time approach. The averaged motor current signal of the electric motors powering the water cooled rolls actively driving the strand represents an indicator for dynamic bulging.

Continuous casting of steel



Molten steel is poured from the ladle into the tundish, a reservoir of liquid steel. From the tundish liquid steel flows through a valve and a pipe – the submerged entry nozzle, SEN – into the water cooled mold. Inside the mold the solidification of liquid steel starts and a container with liquid steel inside is formed by the already solidified steel.

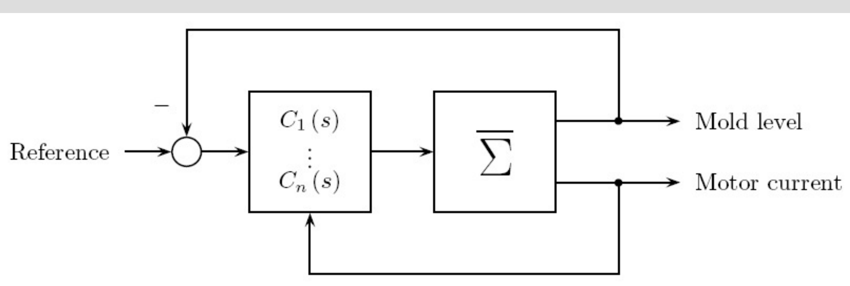
The generated strand is afterwards transported out of the mold and downwards the plant by rolls, while under constant cooling solidification is in progress. Without any interruption of the process finally the strand can be cut into slabs and removed from the plant.

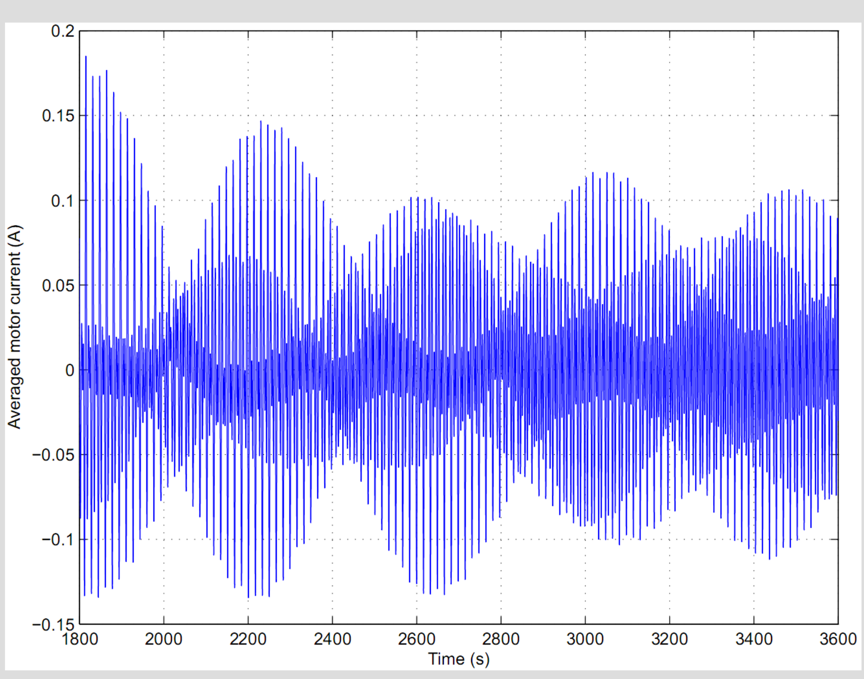
The reason for bulging can be found in the ferrostatic pressure changing the reservoir for liquid steel inside the strand between the around 100 water cooled rolls – some of them activiely driving the strand. Especially dynamic bulging occurs in some plants more likely than in others and depends on the materials being produced and the geometrical arrangement of the pinch rolls of the strand.

If the casting speed is not reduced when the mold level shows dynamic bulging tendencies, mold level hunting can develop and cause an outflow of the mold or a burst in the strand shell.

Simplified model of the process

Since the simulator is too complex and linear matrix inequalities have to be solved for the determination of the switching rule and the filter matrices, a simplified model has to be calculated for control design and a tradeoff has to be found between the complexity of the simplified models, the accuracy the models describing the process and the computational power of todays computers.





The block Σ represents the model of the process. The loop is closed via the measured mold level and one PID-controller for each casting speed.

While for the lowest and the medium casting speed the behaviour of the continuous casting plant is stable, for the fastest one this is not correct. In contrast currently only one PID-controller is used at a continuous casting plant in the simplest case.

On the left side the averaged motor current signal is shown for a casting speed of 1.0 m/min and 30 minutes. An alternative to the direct usage of this signal is to develop models based on a kind of envelope

$$\begin{aligned}\dot{x}(t) &= A_i\,x(t) \qquad i=1\ldots3\\ x(0) &= x_0\\ y(t) &= c_i^T\,x(t)\end{aligned}$$

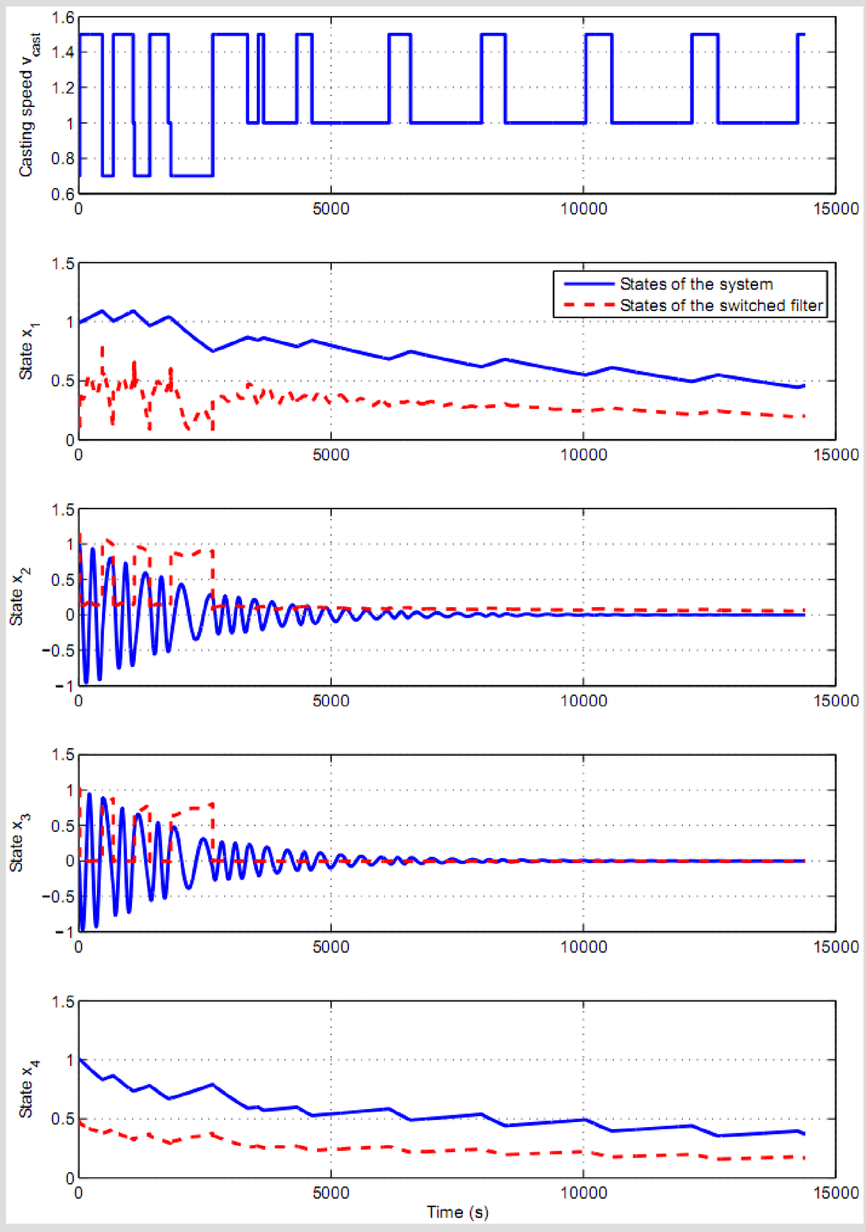
assumed to take the following structure

$$A_i = \begin{bmatrix}\alpha_{i,1} & 0 & 0\\ 0 & \alpha_{i,2} & \omega_i\\ 0 & -\omega_i & \alpha_{i,2}\end{bmatrix}$$

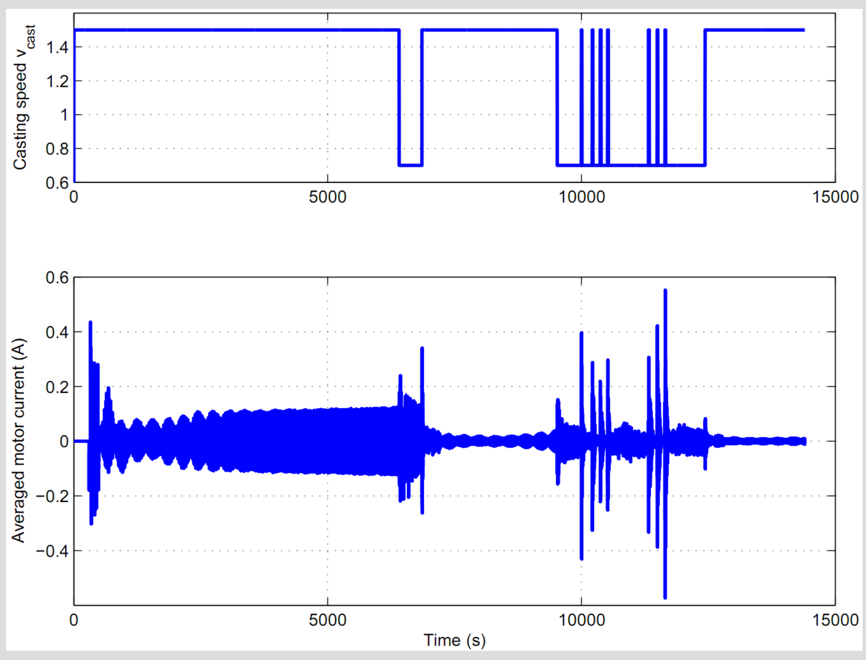
$$c_i^T = \begin{bmatrix}c_{i,1} & 0 & c_{i,2}\end{bmatrix}$$

$$x_0^T = \begin{bmatrix}x_{0,1} & x_{0,2} & 0\end{bmatrix}$$

Dynamic output feedback control



Casting speed, evolution of the states of the developed simplified model and the states of the switched filter



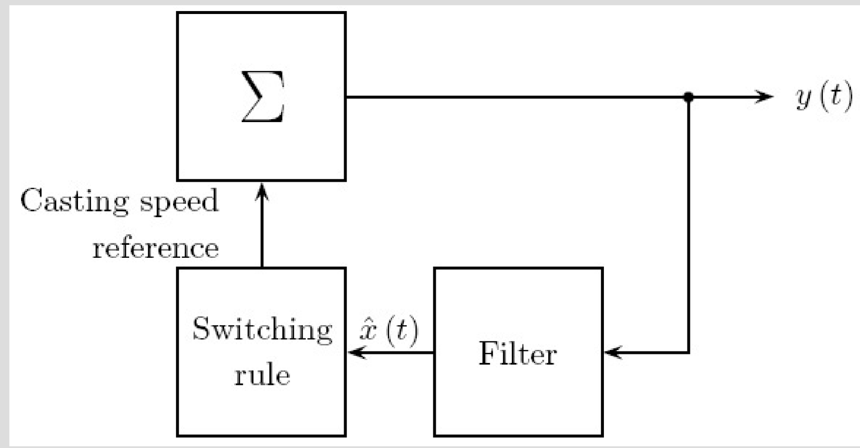
Casting speed and averaged motor current (Simulator)

By using this method the aim is to find an output feedback control law of the form

$$\sigma(t) = u\left(y_{[0\,t]}\right)$$

solely dependent on the available measurements, such that the origin becomes a globally asymptotically stable equilibrium point.

An extension of the closed loop Σ (model and PID-controller) using a switched filter is needed, since only the measured averaged motor current signal is available on both real plants and on the simulator.



In case of the developed simplified model the algorithm only tries to asymptotically stabilize the output as quickly as possible. The casting speed is not taken into account. Therefore a further state is added to maximize the average casting speed:

$$A_i = \begin{bmatrix}\alpha_{i,1} & 0 & 0 & 0\\ 0 & \alpha_{i,2} & \omega_i & 0\\ 0 & -\omega_i & \alpha_{i,2} & 0\\ 0 & 0 & 0 & \alpha_{i,4}\end{bmatrix}$$

$$c_i^T = \begin{bmatrix}c_{i,1} & 0 & c_{i,2} & 0\\ 0 & 0 & 0 & c_{i,4}\end{bmatrix}$$

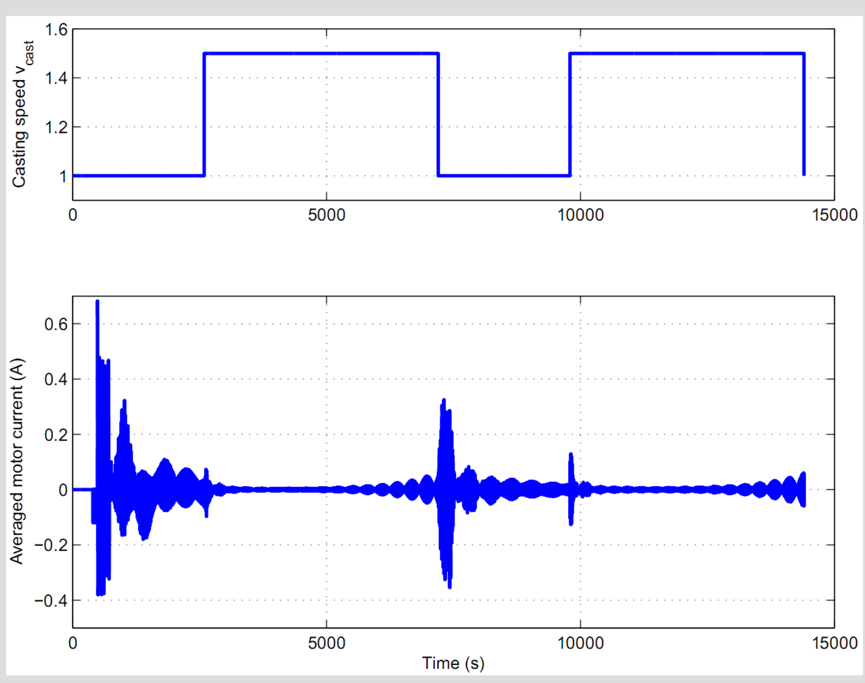
The introduced state does nothing else than to penalize the use of the lowest and the medium casting speed.

Because of conflicting targets and for this reason a frequent change of the casting speed, it is useful to introduce a hysteresis.

The desired behaviour can be realized:

- The lowest casting speed is only applied when the mold level shows major oscillations. This mode should therefore be reserved for extreme and emergency situtations.
- The operation time of a given mode raises from several hundred to some thousand seconds.

Average dwell time approach



By using the method of dynamic output feedback control the decision on the mode to be used was taken using the output. Another way to achieve a switching strategy is offered by the average dwell time approach. The switching control law is only time-dependent, the output signal is not fed back.

Only the two higher casting speeds will be considered here, since an implemenation of the average dwell time approach is much easier and meaningful with two instead of three modes.

The maximum value of the average casting speed can be calculated based on the damping coefficents of the simplified model. However existing oscillations can not be damped and disturbances respectively model uncertaintes can cause instability.

The performance on the simulator is illustrated in the above Figure. In this case the average casting speed is 1.3 m/min and one can see a significant reduction of the oscillations.

The comparison of both applied methods shows that in case of dynamic output feedback control all three modes are in use, while the length of time during which the stable mode representing a casting speed of 1.0 m/min is used, is longer in case of the average dwell time approach.

Although a filtering of the reference of the casting speed is done in the case of both developed methods, peaks in the averaged motor current signal can be detected at the time of switching. However, such peaks do not occur on real plants. Instead, the speed is adjusted more or less slowly to the reference.

Conclusion and Outlook

The presented methods enable us to operate a continuous casting plant stable and at a casting speed for which a stable behaviour is no longer possible with a single PID-controller. An increase in the average casting speed is achieved both by using the developed simplified model as well as on the simulator by an intermittent, unstable operation of the plant. A further advantage results from the availability of the necessary measures. There are no additional costs due to further measuring devices.

While for a casting speed of 1.1 m/min, we do not have the ability to stabilise the behaviour of the available simulator with a single PID-controller, with the method of dynamic output feedback control as well as with the average dwell time approach it is possible to reach a casting speed of about 1.3 m/min.

Both methods provide the necessary scope for design. For example, the adaption of the factor to realise the hysteresis when using the method of dynamic output feedback control to the quality requirements represents one of these points. The adjustment of the cycle duration of the switching signal would be imaginable in the environment of the average dwell time approach.

An other possibility for development is the combination of both methods. One could for example choose a constant cycle duration, while the ratio between pulse and pause of the switching signal is adjusted in connection with the periodic oscillations of the mold level. With a limited number of switching operations, it would be possible to stabilize the process of continuous casting.