Switched MPC Based on Clogging Detection in Continuous Casting Process

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Abstract: Nozzle clogging contributes heavily to quality issues seen during the process of continuous casting. The presence of clogging in the Submerged Entry Nozzle (SEN) can significantly change the flow patterns in the mould and therefore impact the quality of the steel product. Also, there is a high risk of inclusions due to parts of the clogging material breaking off and entering the mould. In this paper, we propose a new sensor setup that allows us to detect clogging in the SEN by monitoring the angle of the exiting jet. Based on this clog detection setup, a switched MPC controller is used to keep the angle of the exiting jet between the optimum ranges using an Electromagnetic Brake. This allows the controller to keep the angle of the jet in the optimum range even when clogging occurs in the nozzle. Experimental data from a laboratory scale continuous caster is used to derive the models for the controller.

Keywords: Flow Control, Tomography, Switched MPC, Hammerstein-Wiener Model

1. INTRODUCTION

Continuous casting refers to the process of transforming liquid metal to solid metal. The process begins with liquid metal being poured from a ladle to a ‘tundish’. A Submerged Entry Nozzle (SEN) is then used for the liquid metal to flow into the mould. The flow rate in the SEN is controlled usually by a stopper rod or sliding gate. The liquid metal is cooled down and a thin solid shell is formed based on the shape of the mould. The strand is then transported using rolls that are cooled by water sprays until the solidification process is complete (Thomas, 2003). Many of the quality issues that are seen in the end product of the steel originate from the fluid flow in the SEN and the mould. Inclusions, meniscus freezing, nozzle clogging are a few of the phenomena that can disturb the flow regime in the mould and therefore affect the end quality of the steel.

Nozzle clogging is one of the main challenges faced by the continuous casting industry as it directly affects the casting operations and the end product quality (Zhang *et al.,* 2008). Clogging in the SEN causes the exiting jet and the flow pattern near the ports of the nozzle to change, which can cause mould level variations and unstable flow (Bai *et al.,* 2000). Furthermore, this proves to be a challenge when designing simple control loops for the process, as the dynamics of the system changes when clogging is introduced. The optimum flow pattern in the mould is a symmetric double roll flow compared to the single roll flow pattern (see Fig.2). The double roll flow allows impurities to rise to the surface which decreases slug entrainment in the solid steel (Cukierski *et al.,* 2007). SEN clogging has been shown to disturb this optimum flow pattern, especially by affecting the impingement of the jet into the mould. It has been seen in (Cho *et al.,* 2012) that due to clogging on one side of the nozzle, the flow exiting the outlet on the other side is increased. This results in a deeper jet impingement in the mould.

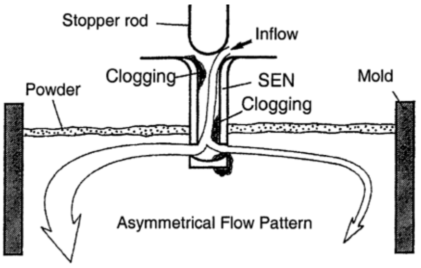

Figure 1: Effect of SEN clogging (Yuan *et al.,* 2003)

The majority of control loops currently implemented in the continuous casting process are limited to temperature field control (see e.g. Belavý *et al.,* 2015) and mould level control. The authors of this paper have previously implemented a sensor setup that uses the whole flow pattern in the mould (Abouelazayem *et al.,* 2019). The sensor setup provides the velocity fields inside the mould which correlates to the flow patterns seen in the mould. The objective of the controller in (Abouelazayem *et al.,* 2019) was to maintain the angle of the exiting jet between the optimum ranges using an Electromagnetic Brake (EMBr) as the actuator. The controller was successful in maintaining the optimum range while rejecting the disturbance from simulated clogging. In this paper, we are proposing a step further by using experimental data from both clogged and unclogged nozzles, using the sensor setup to detect when clogging occurs, and creating a switched MPC that can control the angle of the jet in both the unclogged and clogged scenarios.

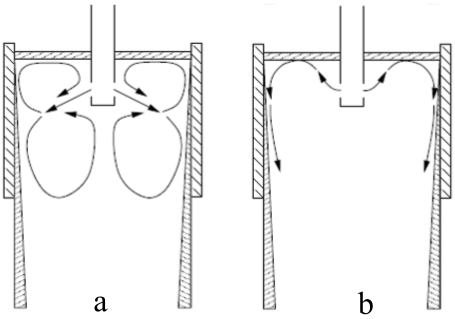

Figure 2: a) Double roll flow pattern, b) Single roll flow pattern

2. SYSTEM DESCRIPTION

2.1 Experimental Setup

The Mini-LIMMCAST is an experimental setup of the continuous casting process located in Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden Germany. Gallium-Indium-Tin (GaInSn) is used instead of liquid steel. GaInSn is poured from the 'tundish' into a glass mould through the Submerged Entry Nozzle. The stopper rod position is kept constant during the experiments in order to have a constant flow rate into the mould. The setup operates in a closed circle where the liquid from the mould continues to a reservoir from which it is then pumped again into the 'tundish'.

2.2 Measurement System

The continuous casting process operates under harsh conditions such as high temperatures which limits the use of many conventional sensors. Furthermore, the opaqueness of the steel itself makes it difficult to get information related to the flow inside. Electromagnetic tomography sensors such as Contactless Inductive Flow Tomography (CIFT) can fill this gap. CIFT has been implemented on the Mini-LIMMCAST setup (Ratajczak *et al.,* 2016) and the velocity fields of the mould were successfully reconstructed. CIFT utilizes the flow of the conductive liquid by generating a magnetic field which induces current in the mould. The current then induces a magnetic field which is measured by the CIFT sensors. The induced magnetic field is used to reconstruct the velocity fields. The other tomographic modality used in connection with CIFT on the setup is Ultrasonic Doppler Velocimetry (UDV). UDV is based on pulse echo method which allows the velocity fields in the mould to be obtained. CIFT is able to provide finer resolution of the velocity fields in the mould, however the sensor setup still faces some issues when it comes to compensating the effect of changing the magnetic field of the EMBr during measurements. For this reason UDV is used in this paper because it is robust and insensitive to the changing magnetic field of the EMBr. The techniques used in this paper with the UDV will be later implemented with the CIFT as soon as the challenges faced by the effect of the EMBr is resolved.

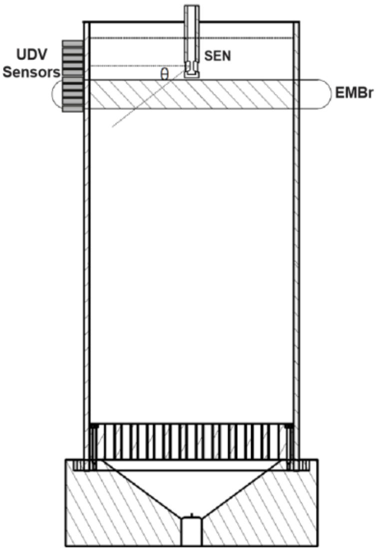

Figure 3: Mini-LIMMCAST Setup

As shown in Fig. 3, UDV sensors are used to measure the horizontal velocities in the mould. Our sign convention will be that velocity has negative sign if the flow moves towards the sensors away from SEN. The figures included in this paper visualize the data from the left half of the mould in both the clogged and unclogged cases. In the case of the unclogged nozzle the right half is approximately symmetrical and in the unclogged it is asymmetrical. The number of sensors is small. For this reason cubic spline interpolation is used to achieve a finer resolution between the sensor positions. Calculation of the jet angle is done in the following way. First the largest velocities with negative sign measured in the region surrounding the SEN outlet are computed. Then linear regression using least squares is used to fit a line that would represent the flow of the jet. In the end, this simple parametrization of the process model using the line representing the flow of the exiting jet allows us to use the raw data from the sensors and avoid any time-consuming reconstruction of the image (see Figs 4 and 5). Horizontal level of the nozzle outlet is considered angle 0º. Angle is positive in anti-clockwise direction.

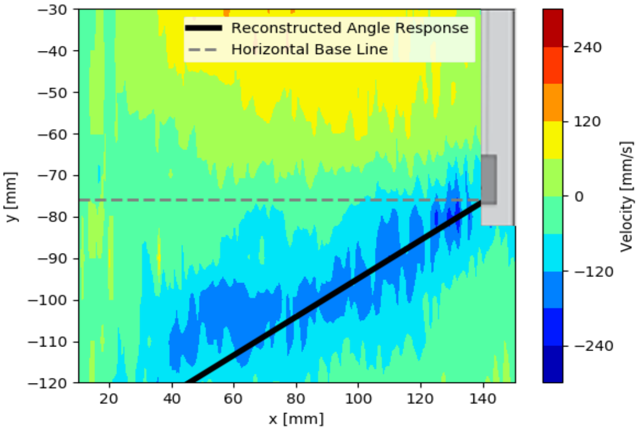

Figure 4: Reconstructed angle response with EMBr turned off

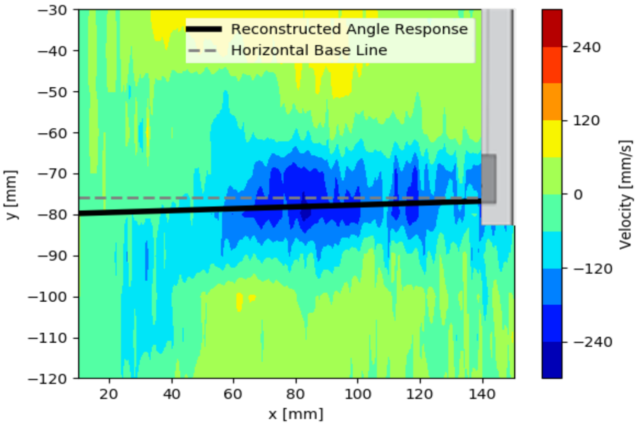

Figure 5: Reconstructed angle response with EMBr current of 450A

2.3 *Electromagnetic Brakes (EMBr)*

In this paper electromagnetic brake is considered as the main actuator. The use of electromagnetic actuation is quite standard in continuous casting. It is used to stabilize the exiting jet from the SEN where the electromagnetic forces can either be static (electromagnetic brakes) or rotating (electromagnetic stirrers). However, a novel feature of our approach is the use of such actuators as continuous actuators in a closed loop control. Usually they are applied in open loop as on/off devices. In this paper the EMBr will be used to control the flow pattern by influencing the exiting jet from the SEN. The static electromagnetic field produced induces current in the conducting liquid. This generates a force that opposes the flow (Chaudhary *et al.*, 2012). The Mini-LIMMCAST includes a wide "single ruler" EMBr which will be used during the experiments. By analysing the flow in the mould during the experiments, it can be seen that the "braking effect" from the EMBr causes the exiting jet to become more horizontal, i.e. it decreases the angle of the jet.

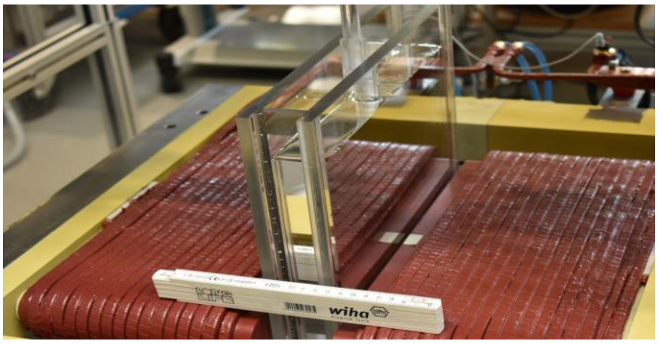

Figure 6: Electromagnetic Brakes (EMBr) in Mini-LIMMCAST setup

3. MODEL DESCRIPTION

As mentioned before the main idea behind the paper is to detect the occurrence of clogging in the SEN using information about the angle of the jet. The first set of experiments conducted on the Mini-LIMMCAST was performed with no apparent clogging in the SEN and it is discussed in a more detail in (Abouelazayem *et al.*, 2019). The second set of experiments was conducted with clogging in the SEN as shown in Fig.7, where clogging is apparent on one side of the mould near the 'tundish' port outlet. In the following sections, it will become clear that the clogging changes the dynamic response of the angle of the jet to the applied current to the EMBr, and therefore different models are needed to describe the dynamic response with SEN clogging and without SEN clogging.

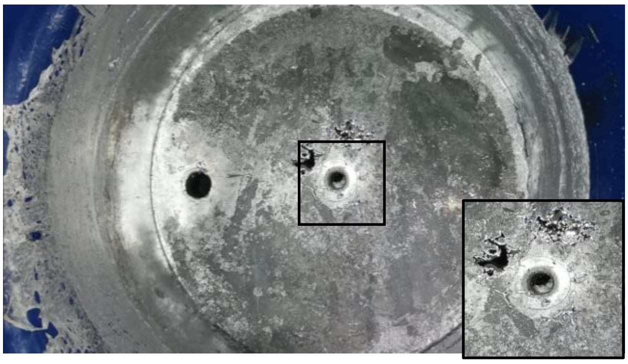

Figure 7: Clogging in the SEN near 'tundish' outlet

3.1 *Model for Normal Operation*

The first set of experiments is used for modelling the dynamic response of the jet angle under normal operation as there was no clogging in the SEN during the measurements. System identification based on measured data was used to find an appropriate model. In the end, the relationship between EMBr current and the jet angle was described by a linear model in the form of a first order model as shown in Eq.1. Fig. 8 compares the response of the model to a series of random step changes to the input which is the current to the EMBr. There is an acceptable fit between the first order model and measured data with a normalized root mean squared error of 80.4%,

$$G_1(s) = \frac{-0.04}{1.4s+1} \tag{1}$$

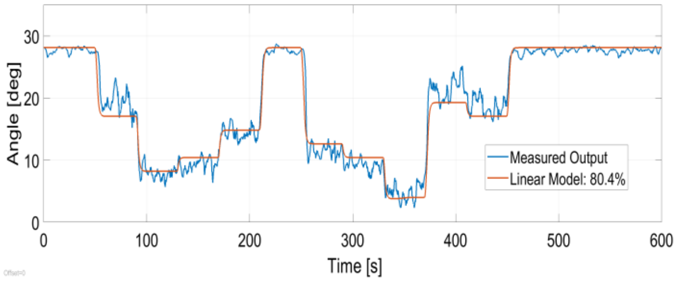

Figure 8: Comparison of simulated model output with measured output

3.2 *Model for Clogged State*

The second set of experiments is used for modelling the dynamic response of the jet angle with clogging in the SEN as seen in Fig.10. The figure compares the response of the models to a series of random step changes to the EMBr current. It becomes clear that the linear model from section

3.1 is no longer sufficient to describe the dynamic response if clogging occurs. There are two fundamental differences. First, the oscillations of the angle are significantly higher with clogging. This is consistent with the results obtained by (Barati et al., 2018) who has found that flow turbulence increases with clogging very significantly. The turbulence kinetic energy may increase by 5 orders of magnitude in the lower part of the nozzle. This increased turbulence is then the source of much increased jet angle oscillations and variance. Second, clogging evidently introduced some additional non-linearity to the response because some parts of the response are described well by linear model while the fit is unsatisfactory in other parts. This increased angle variance can be used to detect the appearance of clogging and this will be discussed in a greater detail in the subsequent sections. The increased nonlinearity can be accounted for by adding a static nonlinearity to the linear model i.e. by using a Wiener model. The linear part of the Wiener model consists of a first order transfer function (see Eq.2.)

$$G_2(s) = \frac{6.3}{1.7s+1} \tag{2}$$

The output of the linear function is fed into a static nonlinear block in order to model the output nonlinearity. In this case, the Wiener model allows us to build on the linear transfer function built in section 3.1 and improve the fidelity of the model by adding a static non-linearity behaviour that has been introduced in the clogging state. Both Eq.1 and 2 have similar absolute values for the time constant. The static nonlinear block in the Wiener model contains a piecewise linear function consisting of 2 breakpoints (see Fig.9). Fig.10 shows that the added nonlinear function improves the performance of the model by 14.74%.

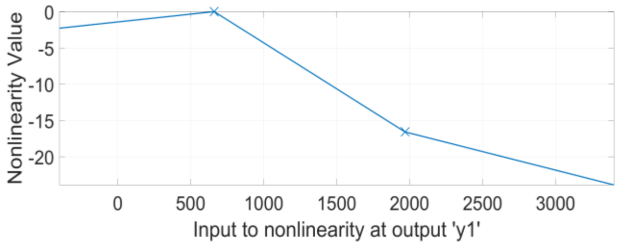

Figure 9: Static nonlinearity using piecewise function

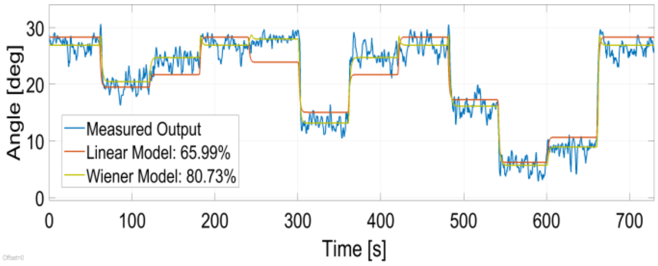

Figure 10: Comparison of simulated model output with measured output

4. CLOG DETECTION

The concept behind using the switched MPC is for the controller to modify its response depending on whether there is clogging or not in the SEN. SEN clogging changes the response of the jet angle to the changes to the current to EMBr as shown in Section 3. The controller should be able to efficiently keep the angle of the jet between the optimum range in both cases of normal operation and during SEN clogging. In order to do so, the controller needs to detect if clogging has occurred during operation using information obtained from the angle of the jet. Fig.11 shows us the angle of the jet for two cases: Case 1 is taken from the first set of experiments where there was no SEN clogging during the measurements. Case 2 is taken from the second set of experiments where the SEN was partially clogged during the measurements as seen in Fig.7. In both figures the EMBr is turned off. It is clear that in the case of clogging, the angle of the jet oscillates more significantly than in the normal operation case. The signal contains higher frequencies. By taking advantage of this behaviour, we can detect the occurrence of clogging during operation by calculating the standard deviation of the signal along a moving window.

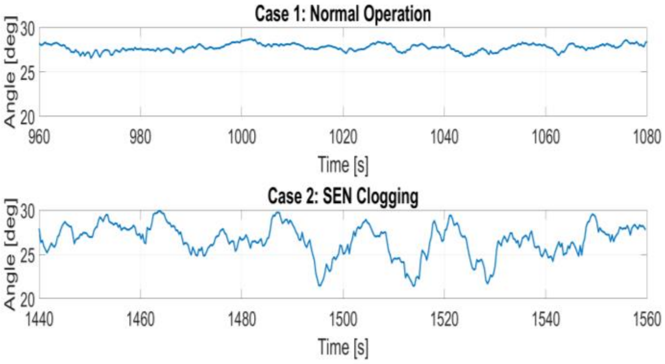

Figure 11: Comparison of jet angle with and without clogging

4.1 High Pass Filter

Varying the current to the EMBr results in sharp transitions in the angle of the jet as can be seen in Fig. 8 and 10. This can cause issues when calculating the standard deviation of the signal in periods where the current is changing. To tackle this issue a high pass filter is used to remove the low frequencies correlated to the changes in the current, so that the clog detection can be done while the EMBr is operational. A Finite Impulse Response (FIR) filter was used with a passband frequency of 0.1 radians/sample and stopband attenuation 60 dB. Fig. 12 shows how the sharp changes in the angle due to current changes are filtered out while maintaining the original frequency of the signal.

4.2 Online Detection

By analysing the standard deviations of both experimental sets, we can see that 80% of the experimental data with clogging have an average standard deviation above 0.6, while the experimental data without clogging have an average standard deviation of 20%. Due to the fact that clogging in the SEN is a slow process, and that the signal from non-clogged system can exhibit a standard deviation of above 0.6

at random moments, the decision on clogging should be done on multiple sequential windows to determine that the increase in standard deviation is constant, and thus confirming the presence of clogging. The controller will only confirm the presence of clogging after 10 sequential windows have been determined with a standard deviation of 0.6 and above. Fig.13 shows clogging detection using the above algorithm. The clogging is detected after 830s from the beginning of the clogging. In the end, clogging is a slow building process that in most cases remains constant until the process is over and the SEN nozzle is replaced with a new one. This allows us to use a larger number of windows in determining the clogging so that it can be confirmed that the increase in standard deviation is due to a constant clogging, rather than random events that have affected the angle.

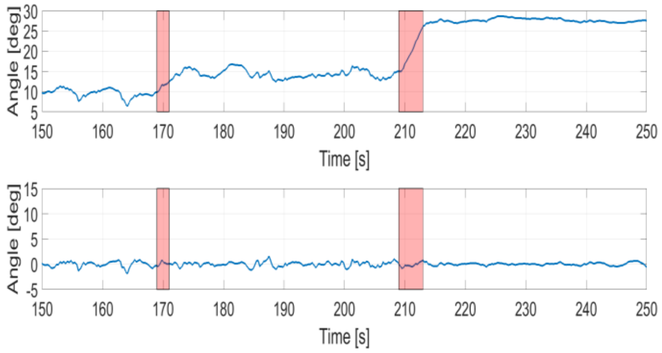

Figure 12: Before and after using high pass filter for jet angle. Highlighted sections show the periods where the current to the EMBr is changed.

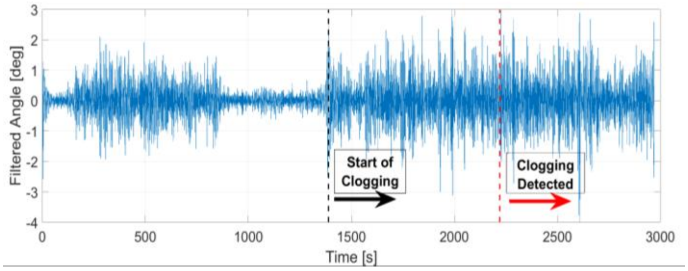

Figure 13: Clog detection using standard deviation of filtered angle

5. CONTROLLER STRUCTURE

Control objective is to keep the jet angle in an optimum range. This is about between 10^0 and 15^0 in the case of our experimental setup. As we can see in section 3, SEN clogging changes the response of the angle to the EMBr. Therefore, two different models are needed to describe the process with clogging and without clogging. By using switched MPC we can have our controller switch between two implicit MPC controllers. First MPC will be based on the model of the system without clogging, while the second MPC will be based on the model of the system with clogging. The switching signal will be the calculated standard deviation of the angle of the jet. This will allow us to select the suitable controller based on the state of the process. Each MPC will then solve a quadratic program to determine the optimal current steps for the current input signals. There are also constraints on the input current to the electromagnetic brake as shown in Eq. 5-7. MPC is known to outperform PID both in constraint handling and range control, therefore making it more suitable for our process. The MPC controller was built using MATLAB. The algorithm begins by converting the models into the below discrete time state space form:

$$x_p(k+1) = A_p x_p(k) + BS_i u_p(k) \tag{3}$$

$$y_p(k) = {S_o}^{-1} C x_p(k) + {S_o}^{-1} D S_i u_p(k) \tag{4}$$

Where A_p, B, C, D are the state-space matrices. S_i and S_o are the input and output scale factors. x_p is the state vector. u_p is the input variables. y_p is the output variables. For the case of the model for clogged state, the Wiener model is linearized at a specific operating point before being converted to the state space form. A quadratic cost function is then used for the optimization problem in order to determine the manipulated variable that should be applied in the future.

$$0 \le u(k+i-1) \le 600 \tag{5}$$

$$-100 \le \Delta u(k+i-1) \le 100 \tag{6}$$

$$10 \le y(k+i-1) \le 15 \tag{7}$$

$$for\ all\ i = \{1, N\}$$

6. RESULTS

Fig.14 shows that from t=0s to t=75s the model for normal operation is used, at t=75s the model is switched to the clogged model to simulate clogging in steel casters. In reality clogging occurs gradually as it builds up with time. Therefore, the change in angle due to clogging will occur at a more gradual pace in comparison to the simulations. We can see that even without the clogging being detected by the controller, the MPC is able to perform the needed action to bring the angle of the jet to the required set point. At t=100s we simulate the clogging being detected and the switching to the second MPC that is designed for the clogging model. It is clear that the transition from the first MPC to the second occurs smoothly with the set point being tracked efficiently. At t=150s the controller is also able to effectively track the set point with the presence of clogging in the process. Fig.15 shows that the switched MPC is able to track the set point without exceeding the constraints on the manipulated variable which is the current in this case.

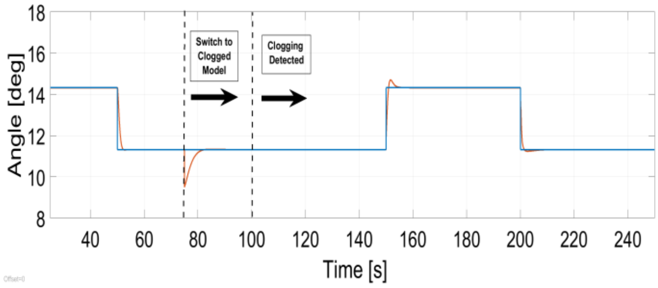

Figure 14: Comparison of model output with set-point reference

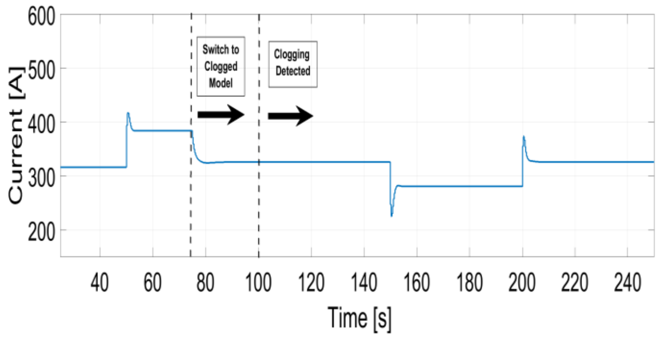

Figure 15: Input current for set-point tracking

7. CONCLUSIONS

The results in this paper demonstrate the use of measured velocity fields to visualize the flow patterns in the mould. Using the measured velocity fields we are able to study certain characteristics of the flow regime, specifically the behaviour of the angle of the jet. We compared the dynamic response of the angle of the jet to the magnetic field of the EMBr in the case of normal operation and in the case of SEN clogging. In the end, the paper showed that clogging can be detected by analysing the standard deviation of the angle during the process. This can be used for fault detection during the casting process. Furthermore, this can be taken a step further by creating a controller that is able to detect the state of clogging and adapt in order to achieve the control objectives. This was done using a switched MPC where two controller were used; one for normal operation, and one for the clogged state. By using the standard deviation of the angle of the jet, the switched MPC was able to achieve the control objectives in both the normal operation and with SEN clogging using the current to the EMBr. In the end, by validating the concept of using velocity fields in the mould to control the flow patterns, the concept will be extended to using tomographic sensors, specifically CIFT sensors which can be implemented in the harsh conditions of a real caster.

ACKNOWLEDGMENTS

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