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The consistency control of mold level in casting process

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A R T I C L E I N F O

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A B S T R A C T

A new multiple periodic disturbance rejection control for casting process is proposed in this paper. Firstly, a high-precision multiple periodic disturbance detection method is designed. The accurate frequencies of the disturbance can be obtained. By using the disturbance observer and a group of filters with additional delay items, multiple periodic disturbance can be suppressed under time-delay environment. Then systematic control design is achieved based on the robust stability analysis. Finally, the efficiency of the proposed method is shown by comparisons between different methods and time-varying disturbance rejection in the consistency control of mold level.

1. Introduction

In the steel industry, the continuous casting is a popular process to solidify the steel. The mold level control strategy is the key factor for ensuring the quality of final product (Jabri et al., 2009). To obtain a good surface quality of the final product, the mold level needs to be maintained stable by adjusting the inflow to the mold. The flow velocity is regulated by the stopper servo system and the mold level controller. A troublesome disturbance called “dynamic bulging (Lee & Yim, 2000; Yoon et al., 2002)” will make the above control difficult. Dynamic bulging shows a periodic disturbance of the mold level, which can lead to interruption of the process (Gruenbacher, Furtmueller, & Del Re, 2007). So, it is very important to suppress the multiple periodic disturbances caused by the dynamic bulging. Repetitive control is used to suppress the load disturbance with unknown periodic (Jolly et al., 1993). Internal model predictor (Furtmueller & Gruenbacher, 2006; Gruenbacher, Furtmueller, & Del Re, 2007) with periodic measurement is applied to suppress the frequency varying disturbance in casting process. Based on the disturbance prediction, adaptive control is designed for periodic disturbance suppressing in casting process (Furtmüller, Colaneri, & Del Re, 2012). These works have made lots of contribution to the consistency control of mold level in casting process. Besides the bulging phenomenon, uneven casting powder adding and not completely melted metal can cause additional load disturbance. Not completely melted metal need to be reduced by temperature control of the ladle and tundish. Casting powder adding needs uniformity for disturbance reduction. If the load disturbance is big enough, the control strategy need to have the ability of suppressing it. Surface waves from the interference can cause detection noise, which need to be filtered out as much as possible by filters. In this paper, this problem is considered in a different perspective: multiple frequencies and load disturbance rejection for time-delay process. Multiple frequencies disturbance widely exists in industries (Chen & Chiu, 2008; Chen & Yang, 2007; Jabri et al., 2008; Kim & Bentsman, 2009; Manayathara, Tsao, & Bentsman, 1996; Yang & Chen, 2008). This type of disturbance can be suppressed by using the disturbance observer method (Li & Bosch, 1993) if there is no time-delay. However, when the time-delay phenomenon exists in the process, many disturbance observer methods may not work well because the disturbance cannot be compensated under phase deviation between the original disturbance and the estimated one. The continuous casting process is a typical system with this feature.

As well-known disturbance rejection methods, time-varying internal model (Marino & Tomei, 2013) and robust adaptive compensation (Brown & Zhang, 2004) are very effective for periodic disturbance suppressing. But they may not be suitable for mold level control in casting process because of the long time-delay. For the time-delay system, many researches have been conducted to improve the step disturbance performance (Albertos & García, 2009; Åström, Hang, & Lim, 1994; Guo & Jutan, 2003; Kaya, 2003; Zhang, Sun, & Xu, 1998; Zhong & Normey-Rico, 2002; Zhong & Li, 2002). Periodic disturbance compensation methods are proposed in Ahn and Chen (2007, 2010). However, there are only a few literatures available for suppressing multiple periodic disturbances in time-delay process. For the small time-delay process, several rejection methods are proposed for the periodic disturbance by estimating the inverse of time-delay, such as

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using a linear approximation method (Zhang et al., 2006), the grey model prediction (Chen, Tung, & Fuh, 2007), or the artificial neural network (Tsai & Tung, 2010). Under the large time-delay, these control method may not achieve satisfied performance as it is difficult to obtain a good prediction of the time-delay inverse. A modified smith predictor control for periodic disturbance reduction is presented (Jabri et al., 2009; Tan, et al, 2017) by modifying Astrom' Smith predictor (Åström et al., 1994). Improved repetitive control (Na et al., 2010) is proposed for time-delay process with periodic disturbance. However, the multiple periodic disturbance is still hardly suppressed in time-delay process.

If the multiple frequency disturbances can be separated into single ones, some single frequency disturbance rejection control principle (Zheng, Fang, & Ren, 2010; Zhou, Wang, & Liu, 2007) may be useful for the multiple frequency disturbance rejection. So, based on the above discussions, a novel and simple approach is proposed for rejecting multiple frequency disturbance under time-delay and applied for the casting process. Firstly, the mold level model is compensated into a stable model. Base on the FFT algorithm, a coarse spectrum of the disturbance can be obtained, by which a group of band-pass filters are designed to filter the disturbance into some independent sinusoidal signals. Then the accurate frequencies can be obtained directly by zero crossing detection. Based on the disturbance observe, a group of band-pass filters are applied to separate the multiple periodic disturbance into single ones. Then, additional delay items are added to compensate the disturbance phase for each frequency. Finally, the multiple periodic disturbance will be compensated in the feedback loop. The systematic controller design is achieved based on the robust stability analysis. Finally, the robustness is studied and the efficiency of the proposed method is shown by the comparison between the proposed method and disturbance compensation controls.

2. Problem description

Consider a continuous casting process in Fig. 1, molten steel flows into the mold through the tundish, and will be solidified by the cooling spray in the end. A solidified shell is thus formed and continuously withdrawn out of the mold. Through the cooling spray, the steel is fully solidified in the end. There is a periodic dynamic bulging in the process that makes the mold level disturbed periodically. The stable mold level is a key factor for the product quality.

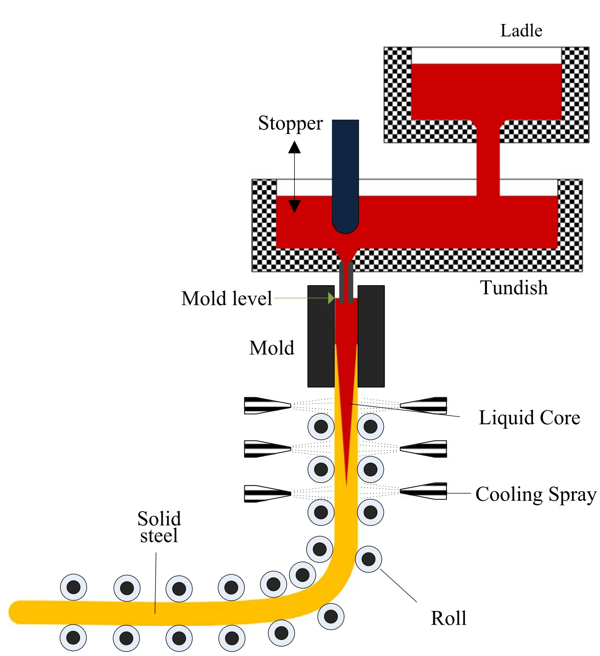

Fig. 1. Continuous casting system.

Based on the dynamics of the continuous casting process, the mold level model of the process can be approximately obtained (Jabri et al., 2009) in Fig. 2. Where u is the control signal, τ is the actuator time constant, G_s is the stopper gain between stopper position and flow, L is the time-delay, Q_{in} and Q_{out} are the flow-rate into and out of the mold, T is the mold section, s is the Laplace variable, y_m is the mold level. As shown in Fig. 2, Q_{out} include two parts: a constant flow-rate Q_c and the periodic disturbance D_p caused by the dynamics bulging. If the mold level y_m is force to a constant, the output of tundish will be smooth. The output measurement model is shown in Fig. 2.

Based on Fig. 2, the transfer function of this process can be obtained:

$$P_n(s) = \frac{G_s e^{-Ls}}{Ts(\tau_a s^2 + \tau_b s + 1)(\tau_s s + 1)} \triangleq P_m(s)e^{-Ls} \tag{1}$$

In Eq. (1), $P_n(s)$ is the nominal model of the mold level. It can be divided into time-delay item e^{-Ls} and dynamic item $P_m(s)$.

The level y_m is affected by the disturbance. PID controller is not sufficient to suppress this disturbance to stabilize the mold level. Even more, the casting process is a time-delay system, the conventional disturbance rejection (Li & Bosch, 1993) may not give satisfactory performance. So it is necessary to develop a multiple periodic disturbance rejection method under time-delay for the application in the casting process.

3. Stabilization and high-precision frequencies detection

The mold level system is an unstable process, for the integral item $1/Ts$. Unstable process is a trouble for periodic disturbance rejection with time delay. For the better control performance, the mold level model is firstly stabled by adding an approximate derivative element as in Fig. 3.

By adding an approximate differential $s/(\alpha s+1)$, the process changes to (2). α is time constant. Then, the plant becomes a stable process. In this type of stable system, the periodic disturbances can be suppressed by the following method.

$$P_n(s) = \frac{G_s e^{-Ls}}{T(\tau_a s^2 + \tau_b s + 1)(\tau_s s + 1)(\alpha s + 1)} \triangleq P_m(s)e^{-Ls} \tag{2}$$

Frequencies detection is very important to the disturbance suppressing. It needs to obtain accurate disturbance frequencies in a short time, about several seconds. Usually, FFT algorithm is an effective method for spectrum analysis and frequencies detection. However, it need much time for precision result. Assume the sample rate is Fs and FFT point number is N. If a precision Fs/N is need, it should take N/Fs seconds to record the data. In the proposed disturbance rejection control method, the requirement for precision is high because of the phase compensation. So big N is needed if using FFT algorithm only. It needs much time and computing resource. A simple and useful frequencies detection method is proposed in this section, which only need small FFT point number and less computing resource. The new method is shown in Fig. 4.

The mold level detection is very important for servo control system. The signal for the mold level sensor contains much noise, which makes differentiator difficult to use. Averaging techniques lead to significant delay-time (Furtmüller et al., 2012). As an important method for frequency detection, the null crossing detection is easy to get wrong results, mainly because the follow reasons: Sensor noise may strongly affect the null crossing detection; Harmonics or multiple frequencies can make the signal waves unsmooth, the null crossing points will have no significant patterns; acquisition of signal may contain bias data caused by the analog components, which makes null crossing points susceptible to the harmonics.

The real mold level changing is a low frequency signal lower than 10 Hz. In this paper, an 8th-order Butterworth low-pass filter is designed for suppressing the sensor noise in our works. The stop