Rejection of Unknown Periodic Load Disturbances in Continuous Steel Casting Process Using Learning Repetitive Control Approach

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Abstract—**This paper describes the design and implementation of a discrete-time repetitive controller for the continuous steel casting process that is used for the rejection of periodic load disturbances with an unknown period. A discrete, recursive scheme is applied to identify the unknown disturbance period and to adaptively change the period setting of the repetitive control algorithm. An experiment was conducted on a full-scale industrial-grade water model. A comparison of the disturbance rejection properties of the repetitive controller with those of PI control is presented. Results that indicate the ease and effectiveness of manual tuning for the rejection of periodic disturbances are then given. Finally, an on-line adaptation of the repetitive controller for the rejection of a disturbance with an unknown period is demonstrated.**

I. Introduction

In most process control applications, PID (proportional integral derivative) controllers perform reasonably well under constant load conditions. Consistent regulation performance is not achieved, however, when the process is subject to fluctuating load disturbances. The features of some continuous steel casting setups result in a periodic component in the load which is seen to be a function of the line speed. In the presence of this periodic component, conventional PI controllers have been found to be incapable of maintaining the level of molten steel in the mold within ± 5 mm. This high-amplitude, periodic mold-level fluctuation has been observed to cause periodic surface defects on the cast steel blooms [2]. A controller that applies the internal model principle [1] may be used to enhance regulation performance of the mold level, because the inclusion of the disturbance dynamics within the controller will effectively cancel the disturbance in the output under feedback control.

The discrete-time repetitive controller of Tomizuka *et al.* [6], which incorporates the internal model principle, is used for cancellation of load disturbances whose period is known. In the case that the period is not known precisely, the structure of the repetitive controller permits on-line tuning of its internal frequency until it matches that of the disturbance for effective cancellation. Tsao and Qian [8] proposed a discrete-time recursive scheme that identifies the period of a periodic signal with resolution better than the signal sampling period.

In this paper, the control-oriented model for the mold level of the continuous steel-casting process is developed. Using this model, the synthesis of the repetitive controller is carried out and implemented on a full-scale industrial-grade water model. The algorithm presented in [8] is used to identify the disturbance frequency on-line and to incorporate it within the controller. This scheme can be successfully implemented in applications where upper and lower bounds on the period of the disturbance signal are known *a priori*. A comparison of the disturbance rejection properties of the repetitive controller with those of PI control is presented. Results that indicate the ease and effectiveness of manual tuning for the rejection of periodic disturbances are then given.

The paper is organized as follows. Section II describes the continuous casting process and specific features that results in periodic load disturbances in the mold level. The mold level control system and modeling of the open-loop process are described in Section III. In Section IV, the design of the discrete-time repetitive controller is presented and the modifications that are made for its implementation in the continuous casting process are described. Section V details a recursive identification scheme that is used to estimate the unknown period of periodic signals. This section also describes the use of the identification scheme to make the repetitive controller adapt to changes in disturbance frequency. Experimental results that demonstrate the disturbance rejection properties of the adaptive repetitive controller are presented in Section VI.

II. Problem Statement

The main components of the continuous casting machine are shown in Fig. 1. Essentially, a casting machine consists of the following: a liquid-metal reservoir and distribution system referred to as tundish, a water-cooled mold, secondary cooling zones supported by containment rolls where external water sprays cool the solidifying steel, and drive rolls that support the solidified plate.

Molten steel is transferred from a ladle into the tundish and the molten metal flow rate from the tundish into the mold is regulated. Control of the mold level is done by hydraulically activated sliding gates at the bottom of the tundish which may

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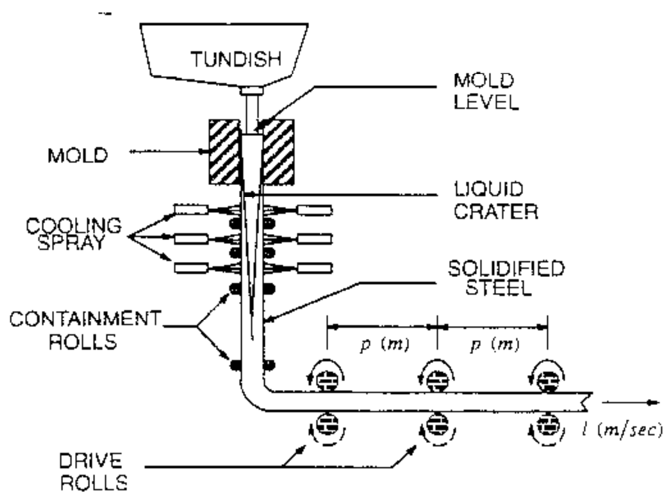

Fig. 1. Schematic of the continuous casting process.

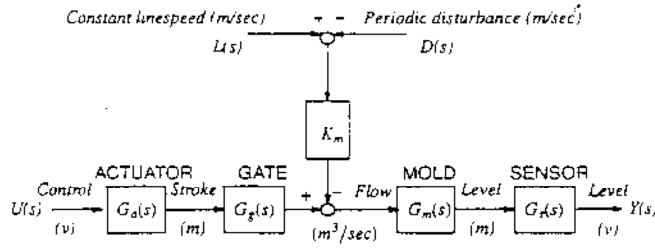

Fig. 2. Block diagram of the open-loop process.

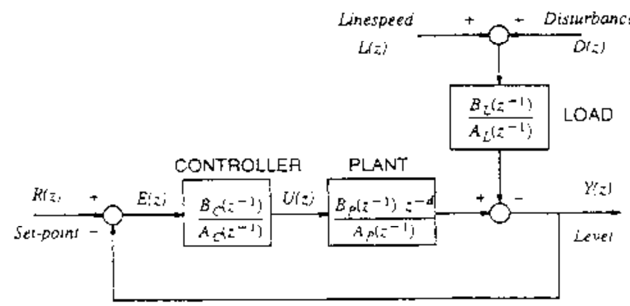

Fig. 3. Discrete block diagram of the closed-loop continuous casting process.

be controlled in either manual or automatic mode. The quality of semi-finished steel depends on regulation of the level of molten steel in the mold and fluctuations in the mold level result in deterioration of the quality of solidified steel [5].

In certain casting arrangements, the drive rolls introduce a periodic disturbance into the system, thereby adversely affecting the regulation of level in the mold. If $l(t)$ is the line speed and p is the spacing between drive rolls, the load disturbance period is approximately equal to $p/l(t)$ s. The problem then consists of canceling the effect of this disturbance on the mold level. In many installations, however, the periodic disturbance is somewhat related to line speed but is not exactly synchronized with the line speed. Therefore, using line speed measurements to directly compensate for the controller period would not be effective.

III. The Mold Level Control System

The level of the molten metal in the mold is sensed by means of thermocouples, radiation detectors, or eddy current meters. On the basis of the sampled level signal, a digital controller is used to generate the control signal. A corresponding analog signal is then used to drive a hydraulic actuator consisting of a servo amplifier connected to a hydraulic unit. The actuator moves sliding gates situated just below the tundish nozzle to compensate for the deviation in the level from the set-point.

A. Modeling of the Open-Loop Process

The block diagram of the open-loop process is shown in Fig. 2. The analog control signal serves as the input to the hydraulic actuator. The output of the actuator can be related to a corresponding displacement of the sliding gates of the tundish valve. Gate characteristics determine the volumetric flow rate of liquid into the mold while the line speed governs the volumetric flow rate out of the mold. The mold acts as a pure integrator, the output of which is the liquid level that is sensed and fed back to the controller. A detailed description of the modeling procedure can be found in a report by Jolly and Bentsman [3].

Frequency response tests are conducted on the actuator and sensor using an HP 3562 dynamic signal analyzer. The actuator is found to be adequately modeled by a first-order transfer function $G_a(s)$ while the sensor may be represented by a second-order transfer function $G_s(s)$. The transfer function $G_g(s)$ of the gate includes a pure transport lag τ, and the transfer function $G_m(s)$ of the mold is a pure integrator. Let K_m be the mold area and ω_a, ω_{s1}, and ω_{s2} be the frequencies of the actuator and sensor, respectively. In the s-domain, the mold level $y(t)$ can be written as a function of the control input $u(t)$, the line speed $l(t)$, and the disturbance $d(t)$ as

$$Y(s) = \frac{K_s K_g K_a e^{-s\tau}}{K_m s(s+\omega_{s1})(s+\omega_{s2})(s+\omega_a)} U(s) - \frac{K_s}{s(s+\omega_{s1})(s+\omega_{s2})}[L(s)+D(s)] \quad (1)$$

where K_s, K_g, and K_a are sensor, gate, and actuator gains, respectively.

B. Mold Level Control Loop

The mold level has to be maintained at a constant value and the corresponding feedback control loop in the discrete domain is shown in Fig. 3. $R(z)$ and $E(z)$ represent the set-point and error signal, respectively. The control signal $U(z)$ and the load disturbances $L(z)$ and $D(z)$ influence the mold level as shown.

From the continuous transfer function in (1), the plant transfer function becomes

$$\frac{B_P(z^{-1})z^{-d}}{A_P(z^{-1})} = \frac{(b_{p0} + B_{p1}z^{-1} + b_{p2}z^{-2} + b_{p3}z^{-3})z^{-d}}{1 + a_{p1}z^{-1} + a_{p2}z^{-2} + a_{p3}z^{-3} + a_{p4}z^{-4}}$$

and the load transfer function is

$$\frac{B_L(z^{-1})}{A_L(z^{-1})} = \frac{n_1 z^{-1} + n_2 z^{-2} + n_3 z^{-3}}{1 + d_1 z^{-1} + d_2 z^{-2} + d_3 z^{-3}}. \quad (2)$$

The coefficients in (2) and the delay d are functions of the sampling period. $B_C(z^{-1})/A_C(z^{-1})$ denotes the controller and $A_L(Z^{-1})$ denotes the dynamics of the sensor. Since the sensor dynamics is stable, the effect of $D(z)$ in steady state is the addition of a periodic disturbance signal to the output.

IV. Design of the Repetitive Controller

If the frequency of the disturbance dynamics $D(z)$ is known, it should be included in the dynamics of the feedback controller to effectively cancel the disturbance in the output. The discrete-time repetitive controller of Tomizuka *et al.* [6] which is based on the internal model principle [1] includes the dynamics of $D(z)$ within the controller structure.

A. Discrete-Time Repetitive Controller

Consider a periodic disturbance signal $D(z)$ with a period T_d seconds. If ΔT is the sampling period in seconds, then $D(z)$ may be generated as the output of a feedback loop that has $(1-z^{-N})$ as its characteristic polynomial [6], where $N = T_d/\Delta T$. The internal model principle requires the denominator $A_C(z^{-1})$ of the controller to include the dynamics of $D(z)$.

Consider an asymptotically stable open-loop plant represented by $B(z^{-1})z^{-d}/A(z^{-1})$ where

$$B(z^{-1}) = b_0 + b_1 z^{-1} + \cdots + b_{nb} z^{-nb}$$

and:

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{na} z^{-na}. \qquad (3)$$

If $B^-(z^{-1})$ contains the roots of the numerator $B(z^{-1})$ which are on or outside the unit circle, $B(z^{-1}) = B^-(z^{-1})B^+(z^{-1})$. Tomizuka *et al.* [6] propose a repetitive controller of the form

$$\frac{B_C(z^{-1})}{A_C(z^{-1})} = \frac{R(z^{-1})}{S(z^{-1})(1-z^{-N})}. \qquad (4)$$

It has been shown [6] that the repetitive controller (4) with

$$\frac{R(z^{-1})}{S(z^{-1})} = \left(\frac{K_r}{b}\right) \frac{z^{-N+d-nu}A(z^{-1})[z^{-nu}B^-(z)]}{B^+(z^{-1})} \qquad (5)$$

where nu is the order of $B^-(z^{-1})$, will result in an asymptotically stable closed-loop system provided

$$\left.\begin{array}{l} 0 < K_r < 2 \\ b = (|b_0| + |b_1| + \cdots + |b_{nb}|)^2 \end{array}\right\}.$$

B. Development of the Controller Structure

The open-loop plant $B(z^{-1})z^{-d}/A(z^{-1})$ of (2) is unstable due to the presence of an integrator (the mold). To implement the repetitive controller (4), the open-loop plant must be stabilized. This is done by using a proportional feedback controller with gain K_{st}. The repetitive controller is then implemented for the stabilized plant which is given by

$$\frac{B(z^{-1})z^{-d}}{A(z^{-1})} = \frac{K_{st}B_P(z^{-1})z^{-d}}{A_P(z^{-1}) + K_{st}B(z^{-1})z^{-d}} \qquad (6)$$

and enclosed within the dashed box in Fig. 4.

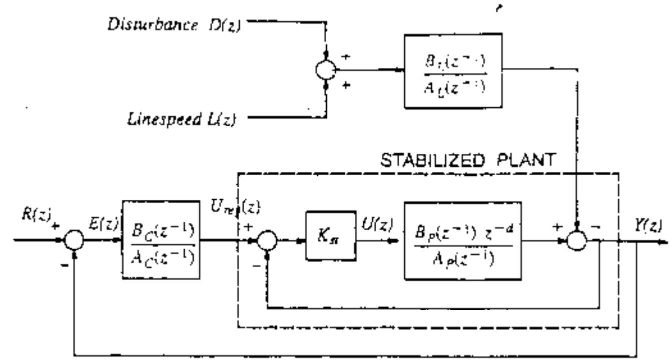

Fig. 4. Block diagram of the stabilized closed-loop plant with repetitive controller.

From (4) and Fig. 4, the repetitive control signal is given by

$$U_{rep}(z) = z^{-N}U_{rep}(z) + \frac{R(z^{-1})}{S(z^{-1})}E(z). \qquad (7)$$

Now define $M(z^{-1}) \triangleq A(z^{-1})[z^{-nu}B^-(z)]$ and $N(z^{-1}) \triangleq B^+(z)$. Using (5) in (7), the repetitive control law becomes

$$U_{rep}(z) = z^{-N}U_{rep}(z) + \left(\frac{K_r}{b}\right)\frac{M(z^{-1})z^{-N+d+nu}}{N(z^{-1})}E(z). \qquad (8)$$

The control signal that is sent to the actual plant is

$$U(z) = K_{st}[U_{rep}(z) - Y(z)]. \qquad (9)$$

To increase robustness of the repetitive controller to model uncertainty, (8) is modified by a zero-phase low-pass noncausal filter

$$\begin{aligned} Q(z^{-1}) &= z^{nf}(0.25 + 0.5z^{-1} + 0.25z^{-2})^{nf} \\ &\triangleq z^{nf}\tilde{Q}(z^{-1}). \end{aligned}$$

The discrete-time repetitive control law of Tsao and Tomizuka [9] is then obtained as

$$\begin{aligned} u_k^{rep} &= Q(q^{-1}) \\ &\quad \cdot \left[u_{k-N}^{rep} + \left(\frac{K_r}{b}\right)\frac{M(q^{-1})}{N(q^{-1})}e_{k-N+d-nu}\right] \\ &= \tilde{Q}(q^{-1}) \\ &\quad \cdot \left[u_{k-N+nf}^{rep} + \left(\frac{K_r}{b}\right)\frac{M(q^{-1})}{N(q^{-1})}e_{k-N+d+nu-nf}\right]. \end{aligned} \qquad (10)$$

In view of (10), the controller implementation is causal, provided $N \geq d + nu + nf$. For low frequency periodic disturbances, typical values of sampling period for the continuous casting process result in values of N that are large enough for causal implementation.

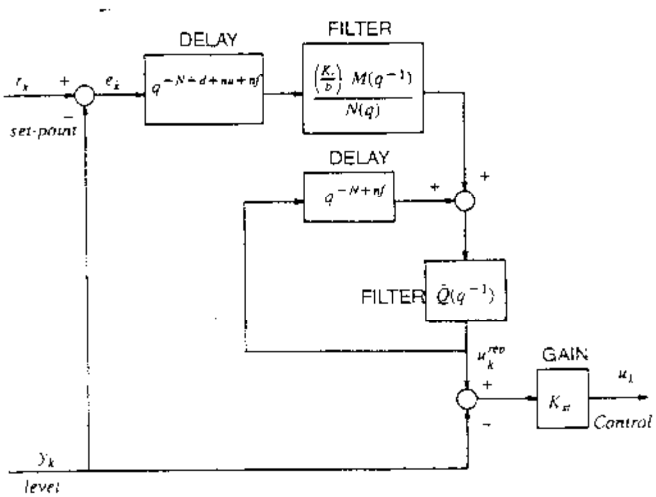

Fig. 5. Structure of the discrete-time repetitive control law for implementation.

C. Implementation of the Repetitive Control Law

The actual control signal that is sent to the actuator is then obtained from (9) and (10) as

$$\begin{aligned} u_k = {} & K_{st}\bar{Q}(q^{-1}) \\ & \cdot \left[u^{rep}_{k-N+nf} + \left(\frac{K_r}{b}\right)\frac{M(q^{-1})}{N(q^{-1})} e_{k-N+d+nu+nf}\right] \\ & - K_{st} y_k. \end{aligned} \tag{11}$$

Fig. 5 shows the structure of the repetitive control law as it is implemented on a digital computer for control of the continuous casting process.

V. Controller Tuning for the Cancellation of the Disturbances with an Unknown Frequency

For effective canceling of the load disturbance, the actual disturbance frequency is required to be known. If ω_d is the frequency of the load disturbance in Hz, then the number of delays N to be introduced in the control law (11) is given by $N = 1/\Delta T \omega_d$.

Implementing the repetitive control law (11) requires delayed values of the repetitive control signal u_k^{rep} and the error e_k. If ω_d is not precisely known, the value of N used in (11) is made to be a tuning parameter during on-line implementation. Tuning N is equivalent to changing the set of delayed control and error values $\{u_{k-N+nf}, e_{k-N+d+nu+nf}\}$ that is used in the control law. The value of N that results in the most reduction of disturbance in mold level is then chosen, thereby setting the dynamics of the repetitive controller close to that of the actual disturbance. Note that the structure of the repetitive control scheme ensures closed-loop stability for any fixed value of N.

A. Recursive Identification of Signal Period

If ω_d is not precisely known, the period identification algorithm proposed by Tsao and Qian [8] is used to estimate the period of the load disturbance. Even if the load disturbance cannot be measured directly, assumption that the system dynamics is time-invariant will ensure that the effect of the disturbance in the feedback loop will be seen in the control signal. Therefore the control signal will have the same period as that of the disturbance.

Consider a periodic signal $u(t)$ that is not identically zero with period τ^*. The identification algorithm is based on the gradient minimization of a quadratic energy function

$$J(\tau) = \frac{1}{2}\int_{t-T_{\max}}^{t} [u(s) - u(s-\tau)]^2\, ds \tag{12}$$

where $T_{\max} > \tau^*$. For the following gradient adaptation algorithms:

1) *Continuous Iteration:*

$$\frac{d\tau}{dt} = -\gamma\frac{\partial J[\tau(t)]}{\partial \tau},\ \tau(0) = \tau_0. \tag{13}$$

2) *Discrete Iteration:*

$$\tau(i+1) = \tau(i) - h\frac{\partial J[\tau(i)]}{\partial \tau},\ \tau(0) = \tau_0. \tag{14}$$

Tsao and Nemani [7] have shown that there exists $\gamma, \sigma, h > 0$ such that if $|\tau_0 - n\tau^*| < \sigma$, then $\tau \to n\tau^*$ as $i \to \infty$ where n is an integer.

The cost function $J(\tau)$ is periodic and has local minima at integer multiples of the base period τ^*. For the iterations (13), (14) to converge to τ^*, the initial condition τ_0 must lie within the concave region containing τ^*.

Since discrete values of the control signal u_k in (11) are known, these data are used in the discrete iteration scheme (14) to determine the period of u_k and consequently that of the load disturbance. Let $\bar{\tau}$ be the known upper bound of the signal period and consider a time period $T_{\max}$ where $T_{\max} > \bar{\tau}$. If ΔT is the sampling period, then let $T_{\max} = L\Delta T$, $\bar{\tau} = \bar{\eta}\Delta T$, and $\tau = \eta\Delta T$. Consider a known set of data $\{u_k: -(L+\bar{\eta}+2) \le k \le -1\}$ and define $\lfloor\eta\rfloor$ as the integer part of the real number η. Then the two adjacent integers of η are $\lfloor\eta\rfloor$ and $\lfloor\eta\rfloor + 1$. The partial derivatives of J in (14) at these integer points are

$$\frac{\partial J(\lfloor\eta\rfloor\Delta T)}{\partial \tau} \cong \sum_{k=\bar{\eta}+1}^{L+\bar{\eta}} (u_k - u_{k-\lfloor\eta\rfloor}) \cdot \frac{u_{k-\lfloor\eta\rfloor+1} - u_{k-\lfloor\eta\rfloor-1}}{2}$$

and

$$\frac{\partial J[(\lfloor\eta\rfloor+1)\Delta T]}{\partial \tau} \cong \sum_{k=\bar{\eta}+1}^{L+\bar{\eta}} (u_k - u_{k-\lfloor\eta\rfloor-1}) \cdot \frac{u_{k-\lfloor\eta\rfloor} - u_{k-\lfloor\eta\rfloor-2}}{2}.$$

The partial derivative of J at the noninteger point η is obtained by a linear interpolation at its two adjacent integer points as

$$\begin{aligned} \frac{\partial J(\eta\Delta T)}{\partial \tau} \cong {} & \frac{\partial J(\lfloor\eta\rfloor\Delta T)}{\partial \tau}(\lfloor\eta\rfloor + 1 - \eta) \\ & + \frac{\partial J[(\lfloor\eta\rfloor+1)\Delta T]}{\partial \tau}(\eta - \lfloor\eta\rfloor) \end{aligned} \tag{15}$$

and the discrete iteration scheme (14) for the period as a function of η becomes

$$\eta(t+1) = \eta(t) - h'\frac{\partial J(\eta \Delta T)}{\partial \tau}$$

where

$$h' = \frac{h}{\Delta T}. \tag{16}$$

In real-time implementation, the iteration period need not coincide with the sampling period since the iteration scheme operates in the background on a fixed set of sampled data.

B. Learning Repetitive Control

In practice, the control signal that is generated by (11) contains high frequency components that result from sensor noise. These components are removed by passing the signal through a second-order low-pass filter with a cutoff frequency greater than the maximum frequency of the periodic disturbance. Using a set of filtered values of the control signal, the iteration scheme (16) can be implemented in the background until the convergence of $\eta(t)$ is obtained. Depending on magnitudes of the signal u_t, the value of the gain h' is set to ensure that $\eta(t)$ converges to the local minimum η^* corresponding to the base period τ^*. On-line implementation of the learning repetitive controller is done by first having a waiting period during which transients in the ill-tuned control signal are allowed to die out. Filtered values of the control signal numbering not less than $(L + \overline{\eta} + 2)$ are then collected after which the estimation routine (16) is carried out. After the new period is obtained, the controller is automatically tuned to the correct period of the disturbance. If the estimated period of the disturbance is not an integer multiple of the sampling period, the closest integer value of the local minimum η^* is used to tune the controller, although the sampling period could have been adjusted to render integer period, as in [8].

VI. Experimental Results

All experiments described in this paper are conducted on a full-scale industrial grade model that is identical in all respects to a generic continuous steel casting arrangement save for the fact that water is used as the medium instead of molten steel. The line speed (load) is emulated by a withdrawal pump that removes water from the mold. Periodic load disturbances are emulated by making the withdrawal pump track sinusoidal signals with frequencies close to that observed in the actual steel casting process. Data collection is done using an analog devices RTI 815 A/D board and the repetitive controller is implemented on an IBM PC 386 compatible. Landau [4] suggests two–nine samples per rise time of the plant step response. Since the rise time of the plant was determined to be approximately 2 s, sampling period of 300 ms is used.

In all experiments, the continuous model used in deriving the repetitive control law is of the form $G_{OL}(s) = K/s(s + \omega_n)(s + \omega_{s1})(s + \omega_{s2})$. The filter $Q(z^{-1})$ with $nf = 10$ is used in all cases to enhance robust stability. $K_{st} = 0.25$ is used to stabilize the open-loop plant and the repetitive control gain K_r is set at 1.0. The control signal is rate limited for the first 200 sampling intervals under repetitive control to prevent excessive transients that result from incorrect initial conditions in implementing the control law (11).

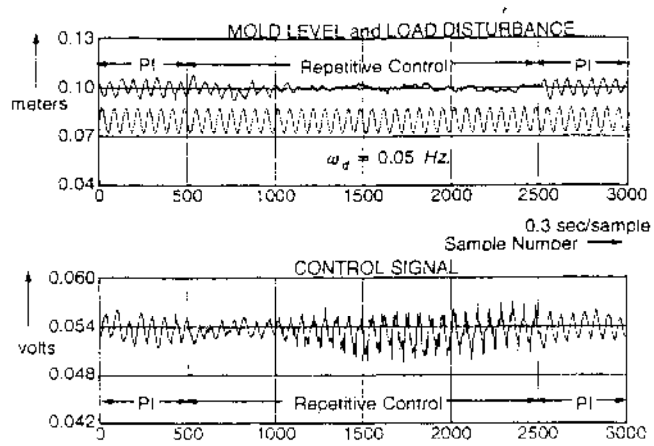

Fig. 6. Regulation of mold level: PI and repetitive control: Model 1.

A. Comparison Between PI and Repetitive Control

Two separate models of the open-loop process are used in the repetitive controller design. Approximate parameters of the continuous model are obtained from frequency response tests conducted on the actuator and sensor using an HP 3562 dynamics signal analyzer. In both instances, controller parameters are derived using the corresponding stabilized discrete models. If the actual period of the disturbance is not an integer multiple of the sampling period, the controller frequency that is used corresponds to the closest integer value of N. For example, if the actual disturbance period T_d is 20 s ($\omega_d = 0.05$ Hz), the finite resolution of sampling period $\Delta T = 0.3$ s restricts N to be 67, corresponding to a controller period of 20.1 s.

Fig. 6 shows the mold level, load disturbance, and control signal under both PI and repetitive control when the parameters of the open-loop model are $K = 1$, $\omega_n = 0.5$ Hz, $\omega_{s1} = 1.0$ Hz, and $\omega_{s2} = 0.159$ Hz. A tuned PI controller is used for the first 500 samples (2.5 min) after which the repetitive controller is used for the next 2000 samples. PI control is used again for the last 500 samples. It is obvious that the repetitive controller rejects the periodic load disturbance much better than PI control.

Mold level, load disturbance, and the control signal when the parameters of the open-loop model are $K = 1$, $\omega_n = 0.75$ Hz, $\omega_{s1} = 1.25$ Hz, and $\omega_{s2} = 0.2$ Hz are shown in Fig. 7. The repetitive controller is seen to exhibit superior regulation in the presence of periodic load disturbance.

B. Performance Under Varying Load Profiles

All subsequent tests are carried out with the same model parameters used in Fig. 7. Under normal operating conditions, the line speed (load) will vary to some degree. The load profile was varied to include different magnitudes of periodic disturbance, but with fixed frequency. In addition, the regulation of the repetitive controller under a constant load

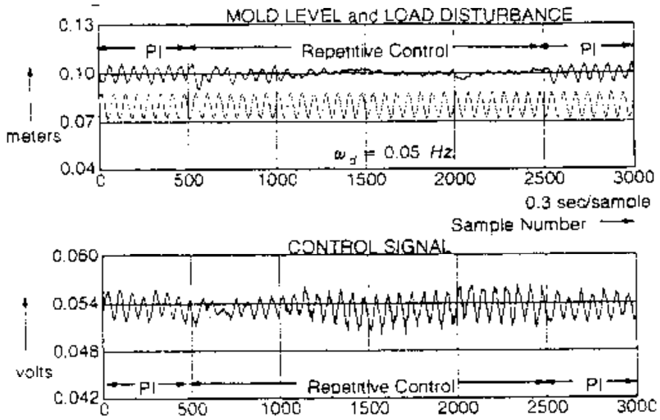

Fig. 7. Regulation of mold level: PI and repetitive control; Model 2.

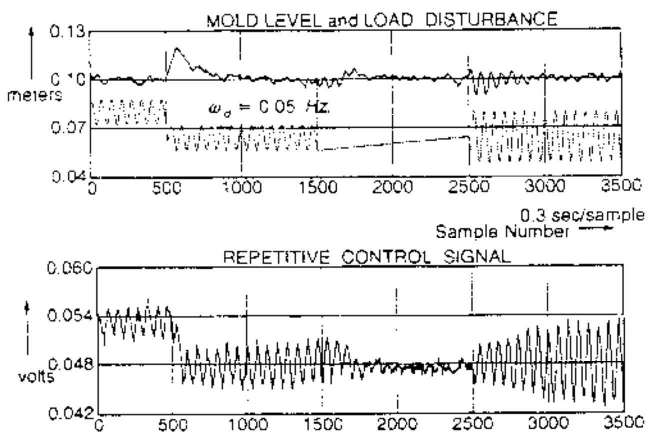

Fig. 8. Regulation under varying load profiles: fixed disturbance frequency.

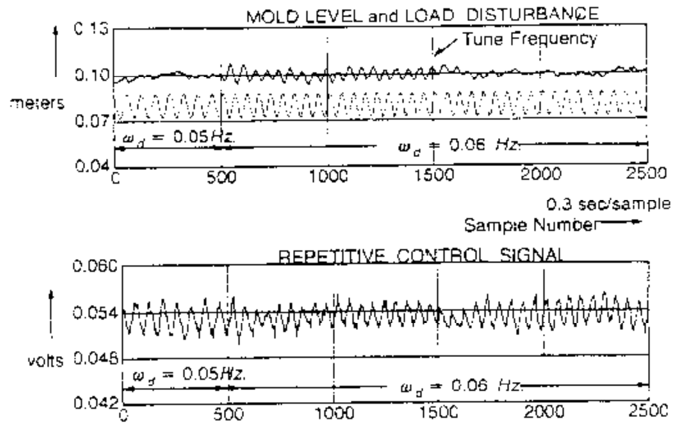

Fig. 9. Manual tuning of controller frequency.

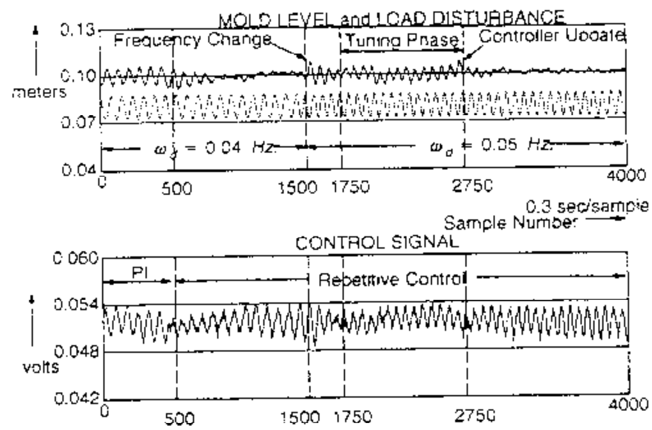

Fig. 10. Regulation of mold level under learning repetitive control.

(no periodic disturbance) is also analyzed, and the results are shown in Fig. 8. The repetitive controller effectively provides asymptotic disturbance rejection and regulates the mold level within ±0.005 m of the set-point.

C. Manual Tuning of the Repetitive Controller

Fig. 9 shows performance of the repetitive controller when the controller frequency is tuned manually. The controller frequency matches that of the disturbance (0.05 Hz) for the first 500 samples, and set-point regulation is seen to be very good. ω_d is then changed to 0.06 Hz and the due to the frequency mismatch, the effect of disturbance is seen in the mold level. After 1500 samples, the controller frequency is manually tuned to match that of the disturbance which is then canceled within 300 samples.

D. Learning Repetitive Control

Tests are conducted on the continuous casting process using the learning repetitive control scheme by varying the frequency of the load disturbance. Filtered values of the control signal are used to identify the disturbance period. Typical values of disturbance frequency in the casting process lie between 0.03–0.07 Hz and the Butterworth filter used for period identification is designed with a cutoff frequency of 0.2 Hz. In Fig. 10, PI control is used for the first 500 samples before the repetitive controller with frequency equal to 0.04 Hz is turned on. Since the actual disturbance frequency is 0.04 Hz for the first 1500 samples, the periodic disturbance is not seen in the output. The disturbance frequency is increased to 0.05 Hz after 1500 samples and the effect of the disturbance is seen in mold level due to frequency mismatch. Filtered values of the control signal between 1750 and 2350 samples (600 steps) are then used to estimate the period of the control signal and the corresponding value of N is used in the controller after 2750 samples.

For convenience, the sampling rate for period identification is taken to be the same as the controller sampling rate, although they need not be equal. Fig. 11 shows the delay N as a function of the iteration step during the tuning phase. The gain h' in the estimation scheme is set to 10 000 and N converges to the correct value within 200 iterations. The controller is automatically tuned to the disturbance frequency after 2750 samples by resetting the controller delay to 67 and as seen in Fig. 10, regulation of the mold level is improved.

VII. Conclusions

A discrete model of the continuous steel casting process is developed. On its basis, a discrete-time repetitive control algorithm that rejects periodic load disturbances in the process output is derived. The low frequency, high-amplitude

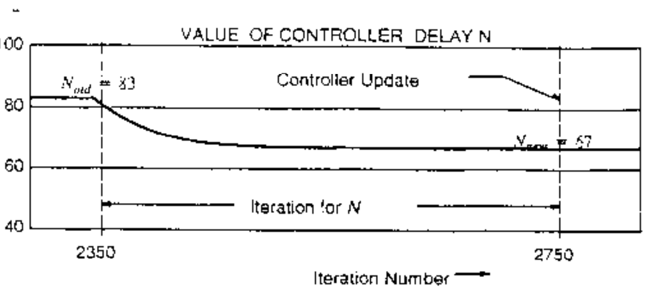

Fig. 11. Estimated value of delay $N4$ during tuning phase.

disturbance is known to generate significant surface defects periodically spaced on the slabs. When frequency of the load disturbance is known, experimental results that demonstrate good disturbance rejection properties of the controller are presented. Experimental results indicate that the repetitive controller may be manually tuned to account for disturbances with unknown period. When the period of the disturbance is not precisely known, a discrete-time recursive scheme is used for identification of the period. Automatic on-line tuning of the controller shows good convergence of the period estimation algorithm resulting in the ability of a repetitive control scheme to effectively regulate mold level under a periodic disturbance of unknown period. Experimental results on a water model show that PI control is not effective in rejecting such disturbances while the repetitive control with adaptively tuned period is able to substantially reduce the mold level fluctuation. Initial implementation at an industrial steel-caster has been carried out as well with promising results.

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