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Iterative Learning Control For Periodic Disturbances in Twin-Roll Strip Casting with Measurement Delay

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Abstract— **We consider the problem of periodic disturbances in the thickness profile of a strip produced using the twin-roll casting process. In twin-roll casting, a strip is produced by pouring molten metal on the surface of two casting rolls that simultaneously cool and compress the strip as they rotate. This rotational motion can produce periodic disturbances in the thickness profile due to angular variations in the shape and thermodynamic characteristics of the rolls. Compensating for these disturbances is further complicated by the fact that there exist large measurement delays between the initial casting and the thickness profile measurement. This paper explores the use of an iterative learning control (ILC) algorithm to reduce the influence of these disturbances on a per-revolution basis. Further consideration is given to managing the measurement delay within the ILC framework. Simulation results show that the proposed controller is able to minimize the effect of the periodic disturbance on the strip thickness profile.**

I. Introduction

Motivation and Problem Definition: Twin-roll casting (TRC) is a near-net shape manufacturing process that is used to produce strips of steel and other metals. During the process, molten metal is poured onto the surface of two casting rolls that simultaneously cool and compress the metal into a strip at close to its final thickness. As the rolls rotate, angular variations in the shape and thermodynamic characteristics of the rolls can create periodic disturbances in the strip's thickness profile. One example of this is when one side of the strip is inadvertently cast thicker than the other due to a change in the relative gap distance between the rolls' edges. This disturbance is called a wedge, and its presence compromises the quality of the final strip. Compensating for this kind of disturbance, however, is complicated by the presence of large delays between the actuation and the measurement of the strip. Fortunately, advanced control techniques offer the ability to improve the quality of the strip by improving the process's disturbance rejection.

Gaps in Literature: Multiple researchers have focused on the stability of the TRC process as well as improving its overall performance [1], [2], [3], [4], [5], [6], [7], [8]. Specifically, many researchers [1], [5], [6], [7] have analyzed the interactions between various process parameters as well as how those interactions affect the steady-state behavior of the process. However, little to no work has been done to reject the disturbances that occur on a per-revolution basis which in turn affect the final thickness profile of the strip.

Interestingly, due to the rotational nature of TRC, the most prominent dynamics of the roll are periodic. This observation, coupled with the large measurement delays that exist in the process, makes learning-based control algorithms an ideal method for addressing the per-revolution disturbances. Iterative learning control (ILC) is a popular control technique for eliminating periodic disturbances that occur in repetitive processes [9], [10], [11]. Originally proposed in the 1980s [12], ILC has been used to improve the tracking performance of a wide variety of systems in the areas of robotics, chemical processing, and manufacturing. An ILC algorithm uses the error signal(s) from the previous trials - or roll revolutions in this case - to generate modifications to the input signal that will be applied during the next trial. Prior work has been conducted to analyze the effects of ILC on the stability of systems with time-varying disturbances [13], [14], and time-delays [15], [16], [17]. Other research has focused on constructing higher-order ILC algorithms that consider trial-to-trial variations [18], [19]. Existing literature, however, does not adequately address the case in which the measurement delay is longer than the period of one trial.

Contribution: In this paper we propose an ILC framework that compensates for the periodic wedge disturbance that occurs on a per-revolution basis in twin-roll casting. We also propose a modification to the ILC framework to accommodate measurement delays longer than a single iteration. We show that the proposed ILC algorithm reduces the wedge by a factor of 2800 in the case of a purely periodic disturbance. We also show that in the case of a slightly aperiodic disturbance, the use of an ILC algorithm with a forgetting factor on the input signal can reduce the wedge by approximately a factor of 2.

Outline: This paper is organized as follows: Sec. II discusses the problem formulation, Sec. III describes the control design, and Sec. IV demonstrates the performance of the proposed controller in simulation. Section V then discusses our conclusions and future work.

II. Problem Formulation

A. Wedge Definition

In twin-roll casting, molten metal is poured onto the surface of the two rolls where it is simultaneously cooled and compressed to form an initial strip. That strip then enters a hot box, as shown in Fig. 1, where it continues to passively cool before entering a hot roll stand that reduces the thickness to its final gauge. Before the strip enters the hot roll stand, the transverse thickness profile is obtained. It is in this location that the wedge is measured by subtracting

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the thickness measurement of one side from the other. To distinguish these sides from one another, we will designate them as the drive side (DS) and the operator side (OS). Then the wedge can be thought of as the DS thickness minus the OS thickness.

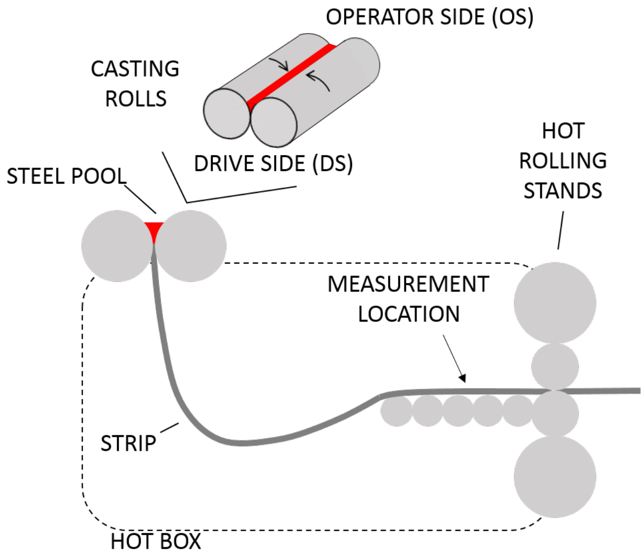

Fig. 1. The steel strip leaves the casting rolls and enters a hotbox where it passively cools before final compression at the hot rolling stand. The wedge measurement is obtained as the strip moves along the table rolls leading to the hot rolling stand.

In a typical cast, the wedge varies as a function of the roll's angular position. As the roll rotates, the changes in the eccentricity of the roll coupled with the thermal variations on the roll's surface can cause the wedge to shift from being biased toward one side to biased toward the other. Then, as the next roll revolution begins, the wedge signal reverts back to being biased toward the first side and the cycle continues. An example of this type of periodic signal is shown in Fig. 2 where the rotational period is approximately 1.5 seconds. Notice that this signal displays behavior that is periodic at both the rotational frequency and twice the rotational frequency. Although the wedge signal is not purely periodic, as can be seen by low frequency variations in the amplitude of the signal, it clearly exhibits strong periodic behavior.

B. Plant Model

The main actuation variable for regulating the thickness profile is the gap created as a result of positioning the casting rolls [20]. As such, we require a plant model that maps how a gap reference signal affects the wedge measurement at the exit of the hot box. We introduce a variable, the tilt, which denotes the difference between the gap distances as measured on the drive side and operator side, respectively.

To identify a system model, we apply a square wave tilt signal, denoted as u and shown in Fig. 3, to the system and measure the resulting wedge signal. The measured wedge

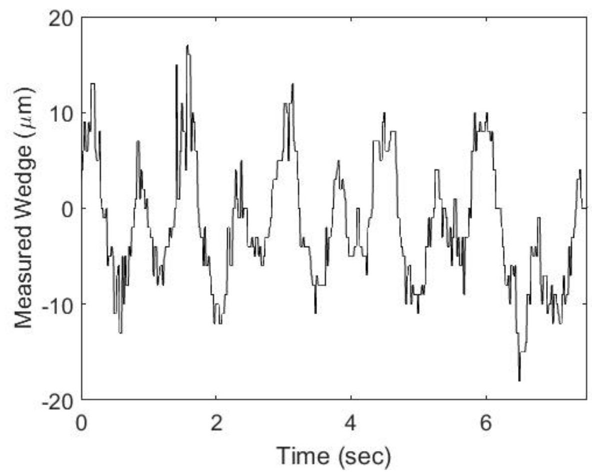

Fig. 2. An example of the measured wedge signal for a TRC process operating with a rotational period of approximately 1.5 seconds.

signal, X_W, is shown in Fig. 4. It is the sum of the input signal, measurement noise, and a periodic disturbance signal, as shown schematically in Fig. 5.

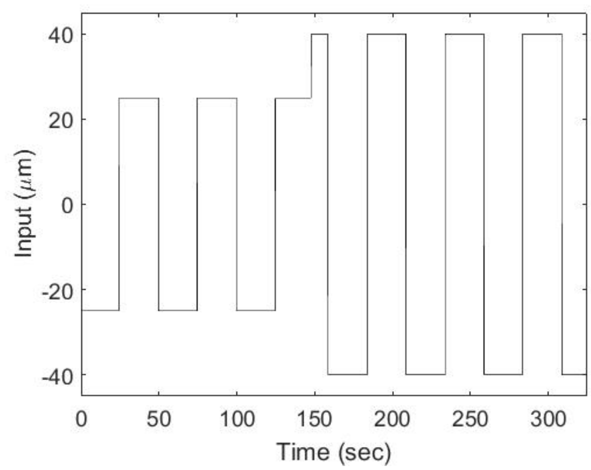

Fig. 3. The input signal used for system identification is a square wave applied to the tilt of the casting rolls. A positive value signifies that the drive side of the casting roll gap is wider than the operator side gap, and vice versa.

The effect of the square wave is apparent in Fig. 4, but the dynamic response is masked by the presence of the disturbance and noise signals. The magnitude plot of the fast Fourier transform of the measured signal is shown in Fig. 6. There are large periodic disturbances at both the rotational frequency (0.68 Hz) and twice the rotational frequency (1.36 Hz). Significant measurement noise also exists above 1.5 Hz, which can hinder the plant identification process. To reduce the effect of these signals, we filter the measured signals using a set of band-stop and low pass filters. The two periodic disturbances are removed in MATLAB using the `filtfilt` command with two third-order, Butterworth band-stop filters:

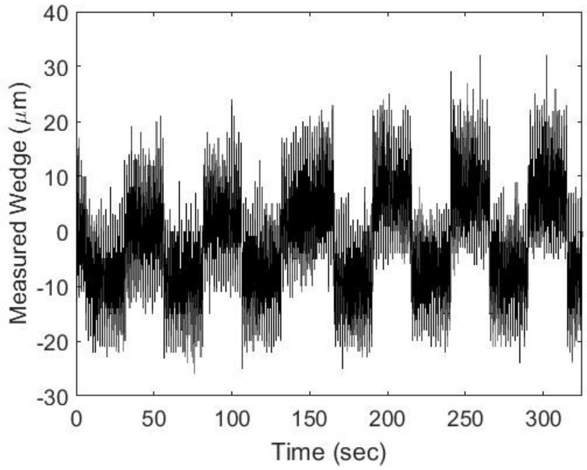

Fig. 4. The magnitude of the measured wedge signal changes in response to the input signal shown in Fig. 3. Positive measurements signify that the drive side of the strip is thicker than the operator side of the strip; negative values mean the operator side is thicker.

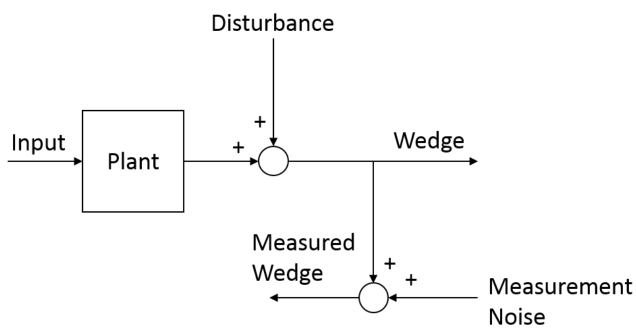

Fig. 5. The measured wedge signal is composed of the plant's response summed with a periodic disturbance and measurement noise.

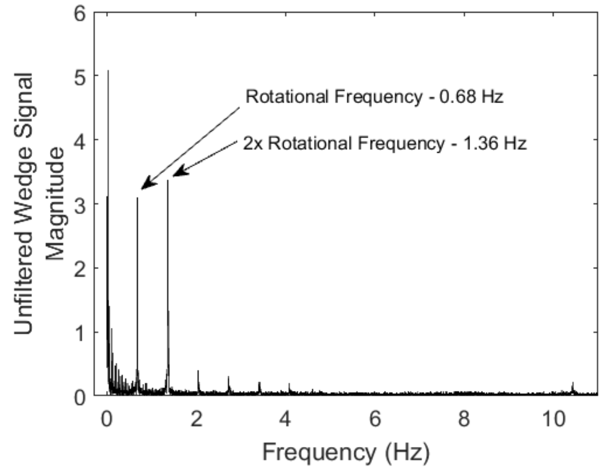

Fig. 6. The fast Fourier transform of the measured wedge signal shows large peaks at the rotational frequency and twice the rotational frequency.

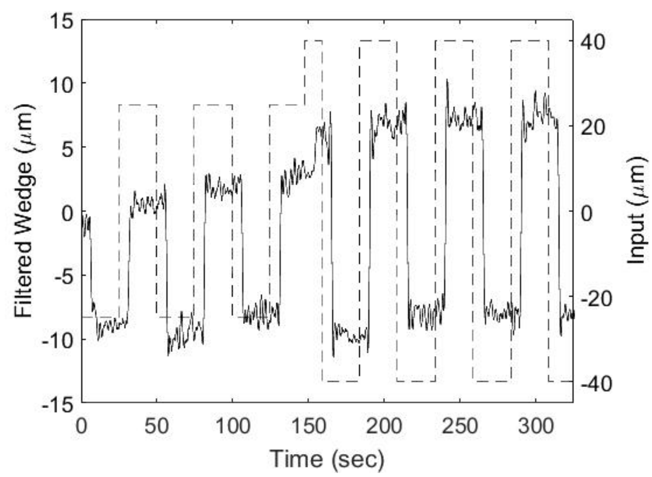

Fig. 7. The filtered wedge signal reflects the steps in the input signal. The solid line is the filtered wedge signal and the dashed line is the input signal from Fig. 3.

one with cutoff frequencies at 3 rad/sec and 6 rad/sec and another with cutoff frequencies at 6 rad/sec and 10 rad/sec. The high frequency noise is then removed in a similar fashion using a sixth-order, low pass Butterworth filter with a cutoff frequency of 9 rad/sec. The resulting filtered signal is shown in Fig. 7.

In addition to the noise, the plant identification is further complicated by the presence of a substantial delay between the tilt dynamics and the wedge measurement. As shown in Fig. 1, the strip leaves the casting rolls and enters the hot box where it forms a loop before being fed into the hot rolling stand. The wedge measurement location is downstream of the loop, on the table rolls that feed the strip into the hot roll stand. The amount of time between when the strip leaves the casting rolls and when the wedge is measured can be long enough such that multiple roll revolutions occur. To identify a plant model to be used for designing an ILC controller, the wedge signal is shifted by approximately 5 roll revolutions to compensate for the measured delay.

The filtered wedge measurement signal, $X_{W,f}$, can then be used to identify the plant model. This is accomplished by assuming that the plant can be described by a polynomial of the form

$$A(z)X_{W,f}(k) = B(z)u(k) \ , \tag{1}$$

where k is the sample index and A and B are polynomials in terms of z, which is the forward shift operator in the k (sample) domain.

Using the SysID Toolbox in MATLAB, we found that a polynomial model given by

$$X_{W,f}(k) = 0.186z^{-671}u(k) \tag{2}$$

is able to achieve a normalized root mean square error fit percentage of 81.65% as shown in Fig. 8.

III. Control Design

The measurement delay discussed in Sec. II introduces a phase lag of $\omega T = 57.3$ radians which makes traditional

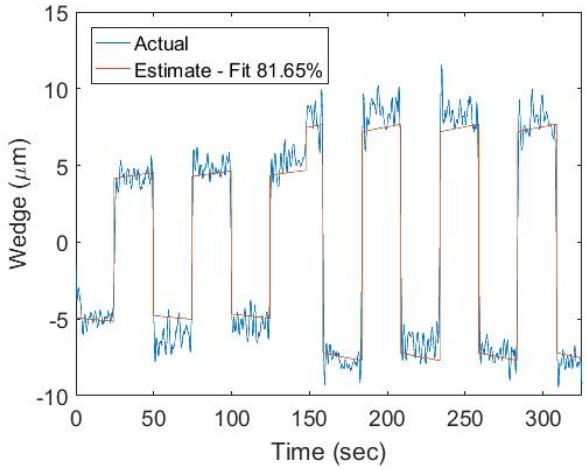

Fig. 8. A comparison of the estimated plant dynamics to the filtered wedge dynamics.

feedback controllers practically infeasible. The identified plant model described in Sec. II can be used to synthesize an iterative learning controller that can overcome the phase lag introduced by the delay. A standard ILC algorithm [9] is given by

$$u_{j+1}(k) = u_j(k) + Le_j(k) \ , \tag{3}$$

where u is the control input at sample k within roll revolution j and e is the error which we define to be the negative of the wedge signal,

$$e_j(k) = -X_W(k) = -(X_{W,f}(k) + D(k)) \ , \tag{4}$$

where D is the periodic disturbance signal. Based on the plant model given in Eqn. (1), the error can be rewritten as

$$e_j(k) = -(B(z)/A(z)u_j(k) + D(k)) \ . \tag{5}$$

This results in a control law given by

$$u_{j+1}(k) = (1 - LB(z)/A(z))u_j(k) - LD(k) \ . \tag{6}$$

Then the convergence condition for the contractive mapping of $u_j(z)$ to $u_{j+1}(z)$ is given by

$$||1 - LB(z)/A(z)||_\infty < 1 \ , \tag{7}$$

where $|| \cdot (z)||_\infty = \max_{-\pi \leq \omega < \pi} | \cdot (e^{i\omega})|$. This mapping ensures that $u_j(z)$ converges to a value that minimizes the tracking error. The condition is satisfied as long as

$$0 \leq L \leq 10.75 \ .$$

A. Delay Compensation

Equation (3) applies if there is no measurement delay. However, as discussed in Sec. II, there does exist a significant measurement delay equal to multiple roll revolutions. To compensate for this, we modify the controller to the form

$$u_{j+n_k+1}(k) = u_j(k) + Lq^{n_k} e_j(k) \ , \tag{8}$$

where q is the forward shift operator in the j domain and $n_k \in \mathbb{N}$ is the number of roll revolutions that occur during the delay, rounded up to the nearest natural number. This modification does not affect the gain bounds because the convergence condition becomes

$$||1 - Lq^{n_k} B(z)/A(z)||_\infty < 1 \ , \tag{9}$$

which results in the same bounds for L.

This type of controller can also be thought of as an ILC algorithm where the iteration period is every n_k revolutions instead of on a per-revolution basis.

IV. Results

To test the performance of the controller designed in Sec. III, we will simulate its performance on the plant model identified in Sec. II with a disturbance signal applied to the plant output as shown in Fig. 5. First, we construct the disturbance signal by subtracting the band-stop filtered wedge signal from the unfiltered wedge signal. The resulting signal is shown in Fig. 9 with a zoomed-in view in Fig. 10. The signal shows some repeatability, but there is also some aperiodic behavior. We first consider a strictly periodic disturbance signal by constructing such a sinusoidal disturbance with frequencies at 0.68 and 1.36 Hz, as shown in Fig. 11.

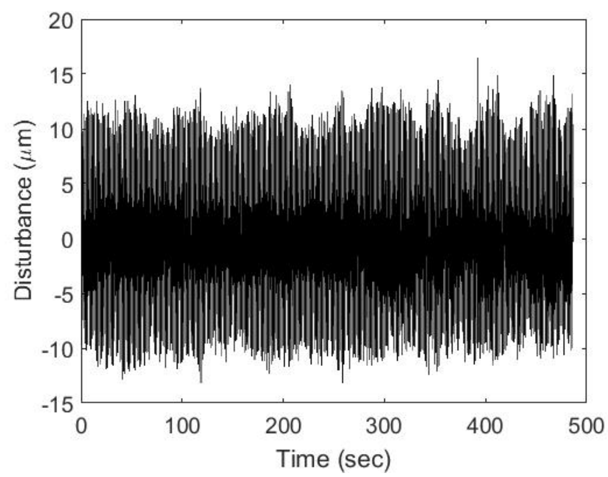

Fig. 9. The disturbance signal affecting the plant.

Then, using the controller outlined in Sec. III, with $L = 5$ results in the the reduction of the wedge signal by a factor of 2800 (in a 2-norm sense) after 25 roll revolutions as shown in Fig. 12. The ILC control input signal quickly converges to its optimal value, and the error signal converges to zero.

Even if we do not compensate explicitly for the aperiodic behavior, a controller with $L = 5$ can still achieve a significant reduction in the error signal as shown in Fig. 13. By combining it with a forgetting factor we can achieve even larger reductions, as shown in Fig. 14. In this example, we modify Eqn. (10) to be

$$u_{j+1}(k) = 0.8u_j(k) + Lq^{n_k} e_j(k) \ , \tag{10}$$

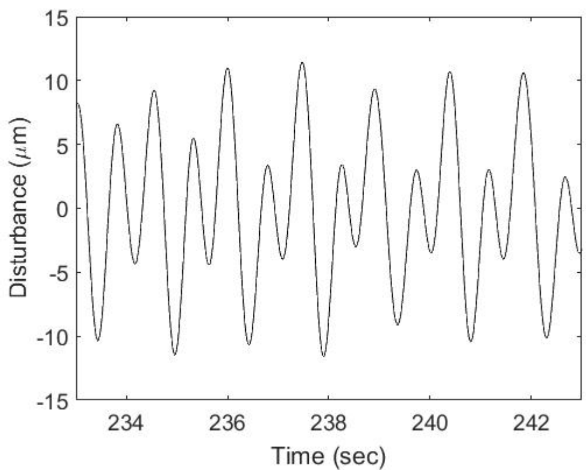

Fig. 10. A zoomed in view of the disturbance signal.

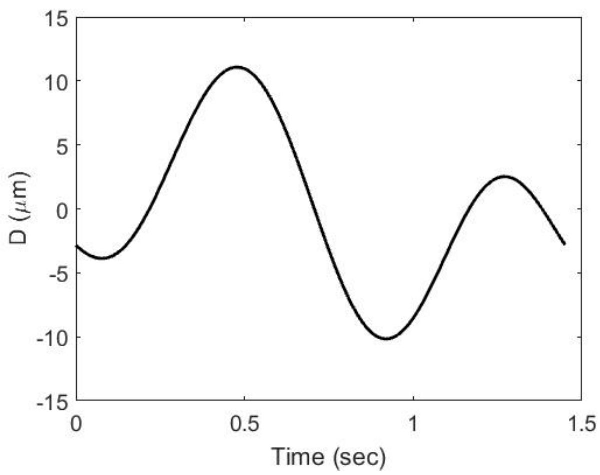

Fig. 11. The wedge signal during the period of one roll revolution.

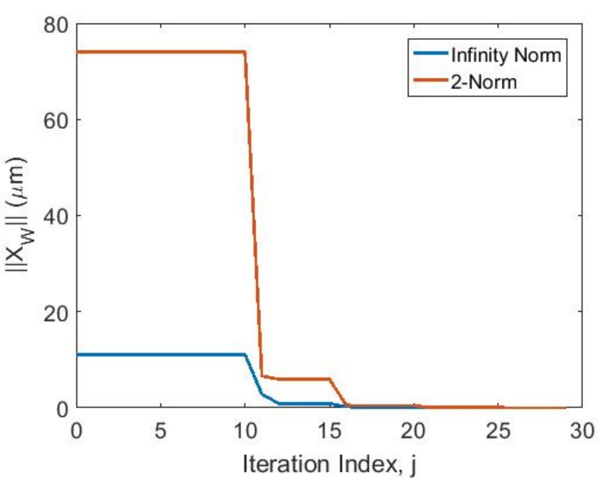

Fig. 12. The norm of the wedge signal after the ILC algorithm is applied to the plant with a strictly periodic disturbance.

where 0.8 is a forgetting factor applied to the previous input signal. On average, this modified algorithm achieves better performance than the previous case that did not include a forgetting factor. In summary, the ILC algorithm is able to reduce the 2-norm of the wedge by approximately a factor of 2, even in the presence of an aperiodic disturbance signal.

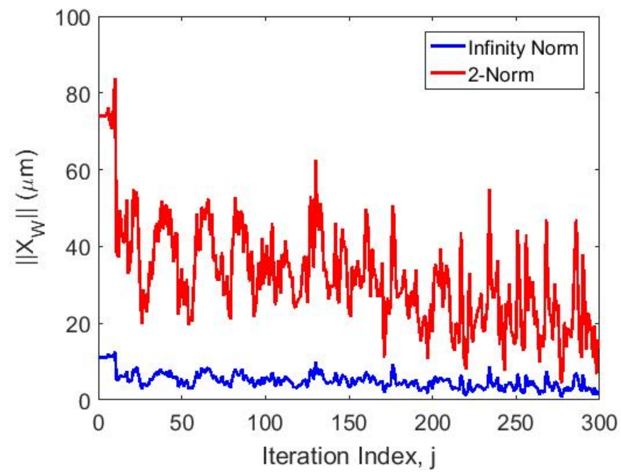

Fig. 13. The norm of the wedge signal after the ILC algorithm is applied to a system where D has some aperiodic behavior similar to the real process.

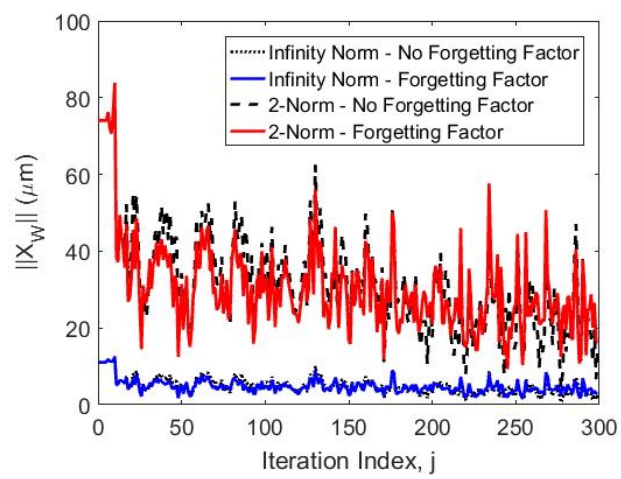

Fig. 14. The norm of the wedge signal after the ILC algorithm with a forgetting factor is applied to a system where D has some aperiodic behavior similar to the real process.

V. Conclusion

In this paper we considered the problem of periodic disturbance rejection with measurement delay in twin-roll casting. The proposed control strategy was able to reduce the influence of the wedge disturbance in simulation. We show that the proposed ILC algorithm, in the case of a strictly periodic disturbance, reduces the wedge by a factor of 2800 after 25 roll revolutions. We also show that in the case of a slightly aperiodic disturbance, the use of a forgetting factor on the input signal in the proposed ILC algorithm adds more robustness to the algorithm and reduces the wedge by a factor of about 2 after 20 revolutions.

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