Two-harmonic Periodic Disturbance Compensation for Dead-Time Processes with Online Identification of Input Delay

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Two-harmonic Periodic Disturbance Compensation for Dead-Time Processes with Online Identification of Input Delay ⋆

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Abstract: As in the case of the Smith predictor, when applied to dynamical systems with delay in the input, the stability of the internal model control (IMC) system can be very sensitive to the mismatch that can occur between the plant delay and the identified delay. In this paper, we propose an online identification technique for the plant with input delay, which is used to adapt an IMC controller designed to reject periodic disturbances consisting of two harmonics. The proposed method is based on wavelet analysis and cross-correlation of the measured output. Moreover, the proposed controller structure introduces a novel analytical approach which makes it suitable for the adaptive application. The practical motivation of the study is to address the delay mismatch that can be caused by approximating time-varying high-order systems by first-order models with input delay. The approach is numerically validated.

Keywords: Delay; vibration control; frequency-domain; time-varying delay; delay estimation;

1. INTRODUCTION

Some processes, mainly industrial processes, require tasks to be performed in a repetitive manner. In such scenarios, these processes may be exposed to periodic disturbances inherently occurring due to wearing over time or manufacture fault of the machine, which in return reflects on the output each cycle during the repetitive task. Moreover, control of such industrial processes may involve time-delays stemming from mainly two different sources. First, the physical setup of the process can impose a time-delay due to sensor placement and communication, for instance, in the case of hot rolling mills (Yuksel et al. (2021a)). Second, delays can be introduced artificially by approximating high-order process dynamics by first-order models with input delay. Such an approximation finds wide applications in the industry since, in general, simple time-delay models can sufficiently capture the main dynamics of complex processes required for the control design. Combined together, these two types of delays can make the overall model of the process to have a time-delay larger than the model time-constant. Therefore, the time-delay becomes essential in the design of control.

A controller that can address both the time-delay and the periodic disturbance can be obtained by modifying several different controller structures. For instance, *repetitive controllers*, which are renowned for their capabilities in periodic output regulations, can be modified to address input time-delays by introducing another delay component to the control-loop as in Omura et al. (2015). Alternatively, the well-known Smith's predictor to compensate time-delays can be modified to reject periodic disturbances as in Zhou et al. (2007).

Another promising controller design approach is the Internal Model Control (IMC) framework. For instance, two different IMC controllers to remove periodic disturbances from systems with dead-time, one utilizing a lumped delay (Yuksel et al. (2021a)) and the other a distributed delay (Yuksel et al. (2021b)), were recently proposed in the open literature. In contrast to the repetitive control, IMC employs the model of the controlled plant instead of the signal model. Under ideal settings, i.e. when the plant and the model perfectly match, the controller can be designed as if the control system is of feedforward.

Under non-ideal conditions, however, as similarly observed for Smith predictors (Morărescu et al. (2007)), the characteristic equation of the IMC applied to a plant with input delay corresponds to a quasipolynomial with two distinct exponential terms i.e.

$$\Delta(s) = N(s) + M_1(s)e^{-s\tau_1} + M_2(s)e^{-s\tau_2} = 0, \qquad (1)$$

where the polynomials $N(s)$ and $M_i(s)$ satisfy $\deg(N(s)) \geq \deg(M_i(s))$ and $\tau_1, \tau_2 > 0,\ i = 1, 2$. Such type of characteristic equations corresponds to those of time-delay systems and

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the stability of the system is assured if all the roots of (1) are located on the left hand plane of the complex plane (Michiels and Niculescu (2007)). It is a known fact that the location of the roots can be very sensitive to the relative difference of the delays (Gu et al. (2005)), leading to a questionable robustness for application. For this reason, delay identification methods and delay adaptive controller designs received attention as an alternative to robust design methods.

As stated in Bjorklund and Ljung (2003), delay identification methods can be grouped under four main classes: (i) methods that derive delay from an approximated model, under which cross-correlation (Azaria and Hertz (1984)) and function estimation (Gawthrop and Nihtilä (1985)) can be found, (ii) methods treating delay as an explicit parameter (Orlov et al. (2003)), (iii) methods that exploit properties of certain responses (Wang et al. (2001)), and finally, (iv) methods with higher-order statistics (Nikias and Pan (1988)).

Forming an adaptive controller for systems with varying or uncertain delays was shown to be possible by replacing the delays with their rational function approximation (De Souza et al. (1988)) or with transport partial differential equations (Bresch-Pietri et al. (2012)). A delay adaptive Smith predictor was also discussed in Bahill (1983).

1.1 Problem Statement

The control problem treated in this paper is to design an adaptive IMC controller that allows a plant, for which its only time-varying property is its input delay, track a given step input meanwhile it is subjected to an output disturbance composed of two harmonics i.e.

$$d(t) = a_1 \sin(\omega_1 t + \phi_1) + a_2 \sin(\omega_2 t + \phi_2) \tag{2}$$

where a_1, a_2 are amplitudes, ω_1, ω_2 are commensurable excitation frequencies and ϕ_1, ϕ_2 are phase shifts. The interest in such a disturbance model stems from the fact that, in the hot rolling process, the disturbance caused by the eccentricity in the rolls can be usually characterized by the sum of two sinusoidal signals.

The paper is organized as follows. Section 2 introduces the structure of the IMC controller and the adaptive modification rule for tuning the parameters. In Section 3, the simulation results of the proposed adaptive control for a prescribed delay change are presented, and in Section 4, the general points of implementation and design are discussed. Section 5 concludes the paper.

2. DELAY ADAPTIVE IMC CONTROLLER

Internal Model Control is the control arrangement depicted in Figure 1, in which the model of the controlled plant is employed in the control loop to compare the actual output of the plant with the estimated one.

IMC was initially and extensively studied by Garcia and Morari (1982). Further extensions of the IMC with various adaptive methods were introduced in Gao et al. (2003) and also in Marino and Tomei (2014) for periodic disturbance rejection and in Hahn et al. (2002) for delay compensation. A robust filter-based IMC design for removing periodic disturbance from systems approximated by first-order models with dead-time was proposed initially in Vyhlídal and Zítek (2001).

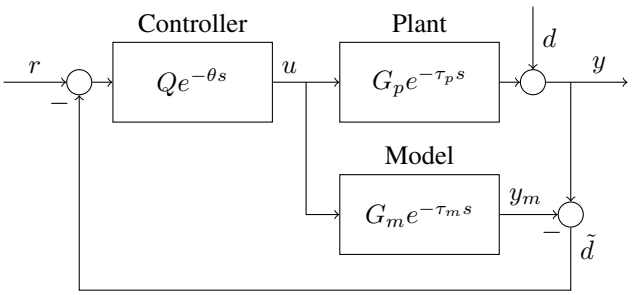

Fig. 1. Conventional internal model control scheme for periodic disturbance compensation

We consider the plant and its model to be composed of two parts, namely, invertible and non-invertible parts. The invertible part, denoted by G_p and G_m for the plant and the model respectively, encapsulates the first-order dynamics. The non-invertible part corresponds to the delays τ_p and τ_m of the plant and the model, respectively. The controller is treated in a similar manner where the transfer function is denoted by Q and the user-definable time-delay by θ.

The *sensitivity transfer function* $S(s)$ of the scheme in Fig. 1 is given as

$$S(s) = \frac{1 - Q(s)G_m(s)e^{-s(\tau_m+\theta)}}{1 + Q(s)(G_p(s)e^{-s(\tau_p+\theta)} - G_m(s)e^{-s(\tau_m+\theta)})}. \tag{3}$$

Following the proposed design by Vyhlídal and Zítek (2001), the transfer function of the controller is given by

$$Q(s) = \frac{1}{G_m(s)} F(s), \tag{4}$$

where $F(s)$ is the filter that needs to be strictly proper.

2.1 Non-adaptive Controller Design

To form a non-adaptive IMC controller that asymptotically tracks the reference r and rejects a periodic disturbance of the form (2), we make the following assumptions:

(i) plant and model transfer functions $G_p(s)$ and $G_m(s)$ are identical i.e.
$$G_p(s) = G_m(s) = \frac{K}{Ts + 1} \tag{5}$$
where K and T are the gain and the time-constant of the dynamics, respectively.
(ii) plant and model time delays τ_p and τ_m are identical (denoted only by τ)
(iii) controller $Q(s)$ is of the form (4)

If all three conditions mentioned above are met, the sensitivity (3) can be simplified to

$$S(s) = 1 - F(s)e^{-s(\tau+\theta)}. \tag{6}$$

In order to track a step input and cancel periodic disturbance (2) we need to make sure that $S(0) = S(j\omega_i) = 0,\ i = 1, 2$. This can be achieved by fulfilling the following set of conditions:

$$\lim_{s\to 0} F(s) = 1, \tag{7}$$

$$|F(j\omega_i)| = 1, \tag{8}$$

$$\arg F(j\omega_i) - \omega_i(\tau + \theta) = 2k\pi, \tag{9}$$

where $k \in \mathbb{Z}$, $i = 1, 2$. To satisfy the conditions, we propose the filter F in the form of

$$F(s) = \frac{p(s) - z(s)}{p(s)}, \tag{10}$$

where polynomials $z(s)$ and $p(s)$ are defined as

$$z(s) = s(s^2 + \omega_1^2)(s^2 + \omega_2^2), \tag{11}$$

$$p(s) = \prod_{i=1}^{5}(s - p_i), \tag{12}$$

$p_i \in \mathbb{C}$ with $\mathrm{Re}(p_i) < 0$.

Consequently, the filter satisfies conditions (7) and (8) since

$$F(j\omega_i) = \frac{p(j\omega_i) - z(j\omega_i)}{p(j\omega_i)} = \frac{p(j\omega_i)}{p(j\omega_i)} = 1, i = 1, 2 \tag{13}$$

which simplifies the condition (9) to

$$\omega_i(\tau + \theta) = 2l_i\pi, i = 1, 2, \tag{14}$$

where $l_1, l_2 \in \mathbb{N}$, due to

$$\arg F(j\omega_i) = \arctan \frac{\mathrm{Im}(F(j\omega_i))}{\mathrm{Re}(F(j\omega_i))} = 0, i = 1, 2. \tag{15}$$

Moreover, since ω_1 and ω_2 are commensurable, i.e. $\exists k_1, k_2 \in \mathbb{Z}$ such that $\frac{\omega_1}{\omega_2} = \frac{k_1}{k_2}$ with $\gcd(k_1, k_2) = 1$, the base frequency defined as $\omega_b := \frac{\omega_i}{k_i}$ yields an equation for the smallest θ satisfying (14):

$$\theta = \frac{2l_b\pi}{\omega_b} - \tau \geq 0, \tag{16}$$

where $l_b = \left\lceil \frac{\tau\omega_b}{2\pi} \right\rceil$.

2.2 Online Delay Identification

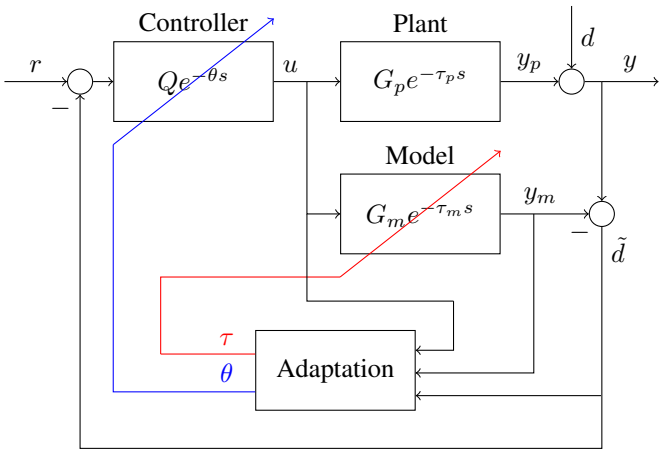

Fig. 2. Proposed adaptive internal model control scheme.

We propose an adaptive scheme shown in Fig. 2 that tracks the changes in time delay and updates the delay parameters in the controller θ and in the model τ_m. The adaptation of the time delay τ_m is based on the discrete cross-correlation of discretized input:

$$\mathbf{u}(t) = [u(t-((N-1)\Delta t), u(t-(N-2)\Delta t), \ldots, u(t)] \tag{17}$$

and estimated output:

$$\tilde{\mathbf{y}}(t) = [\tilde{y}(t-((N-1)\Delta t), [\tilde{y}(t-(N-2)\Delta t), \ldots, \tilde{y}(t)] \tag{18}$$

of the controlled system within a sliding window $T_W = N \cdot \Delta t$:

$$\boldsymbol{\vartheta}[n_\varphi] = (\boldsymbol{u} \star \tilde{\boldsymbol{y}})[n_\varphi] = \sum_{i=1}^{N} \boldsymbol{u}[i] \cdot \tilde{\boldsymbol{y}}[i + n_\varphi]. \tag{19}$$

Where $n_\varphi \in [-N, N] \subset \mathbb{Z}$ (because we use *full* implementation of cross-correlation) is a discrete-time shift between the signals, N is a number of signal samples in the sliding window, and Δt is a discretization time step that satisfies $\Delta t \ll \tau$ and $T_W \gg \varphi(\omega)/\omega$, where $\varphi(\omega)$ is a phase shift of the controlled system G_p

$$\varphi(\omega) = \arg(G(j\omega)e^{-j\omega\tau}) = -\tau\omega - \arctan(T\omega). \tag{20}$$

The estimated output $\tilde{y}(t) = y(t) - \hat{d}(t)$ is a measured output $y(t)$ subtracted by the identified disturbance $\hat{d}(t)$. The disturbance identification is described in the next section.

According to (20) the cross-correlation consists of the delay influence and time constant influence. For the separation of these two parameters, it is also necessary to know the frequency of the signal $\omega = 2\pi f = 2\pi/T_\omega$. The method is derived for single-frequency signal. However, when the signal contains more than one frequency, the cross-correlation is influenced. To avoid the influence of the second frequency, we filter the inputs to the cross-correlation using the low-pass Butterworth filter, where the cutoff frequency ω_c must satisfy $\omega_1 < \omega_c < \omega_2$. After filtering, we use cross-correlation only for the frequency ω_1.

An example of the result of the cross-correlation of periodic signals is visualized in Fig. 3 of the simulation example which follows. The result has several peaks where the position of each peak represents the total time shift between the signals. The distance between these peaks corresponds to the base period of the signals $T_\omega = 2\pi/\omega_1$. For a successful identification of the time shift, it is necessary to have an *a priori* estimate of the time delay $\tilde{\tau}_0$. The error of the time delay estimate must satisfy $|\tau - \tilde{\tau}_0| \ll T_\omega/2$. Otherwise, the identified delay would have an error $k \cdot T_\omega$, $k \in \mathbb{N}$. It is possible to express the total time shift between the signals as the position of a peak:

$$\begin{aligned} \tilde{n} = \underset{n_\varphi}{\mathrm{argmax}} \quad & |\boldsymbol{\vartheta}[n_\varphi]| \\ \text{s.t.} \quad & A \leq n_\varphi \leq B \end{aligned} \tag{21}$$

in a specified range of time shift $n_\varphi \in [A, B] \subset \mathbb{Z}$ using the estimate of time delay, which should narrow the cross-correlation range to identify only one position of a peak. The range is calculated from the intital total time shift estimate $\tilde{\varphi_0}(\tilde{\omega}) = -\tilde{\tau_0} \cdot \tilde{\omega} - \arctan(T \cdot \tilde{\omega})$, where $\tilde{\omega}$ is the identified frequency, and from a period range modificator C:

$$A = \left(\frac{\tilde{\varphi_0}(\tilde{\omega})}{\tilde{\omega}} - C\frac{T_{\tilde{\omega}}}{2} \right) \frac{1}{\Delta t}, \; C \in (0, 1) \tag{22}$$

and

$$B = \left(\frac{\tilde{\varphi_0}(\tilde{\omega})}{\tilde{\omega}} + C\frac{T_{\tilde{\omega}}}{2} \right) \frac{1}{\Delta t}, \; C \in (0, 1). \tag{23}$$

From (20) and (21) it is possible to express the identified time delay $\tilde{\tau}$:

$$\tilde{\tau} = \tilde{n} \cdot \Delta t + \frac{\arctan(T \cdot \tilde{\omega})}{\tilde{\omega}}. \tag{24}$$

The resolution of the peak position is Δt. To improve the accuracy of the peak position, we interpolate the neighborhood of the identified $\tilde{\tau}$ with a cubic spline (visible in the lower graph in Fig. 3). The finer resolution is then possible to obtain

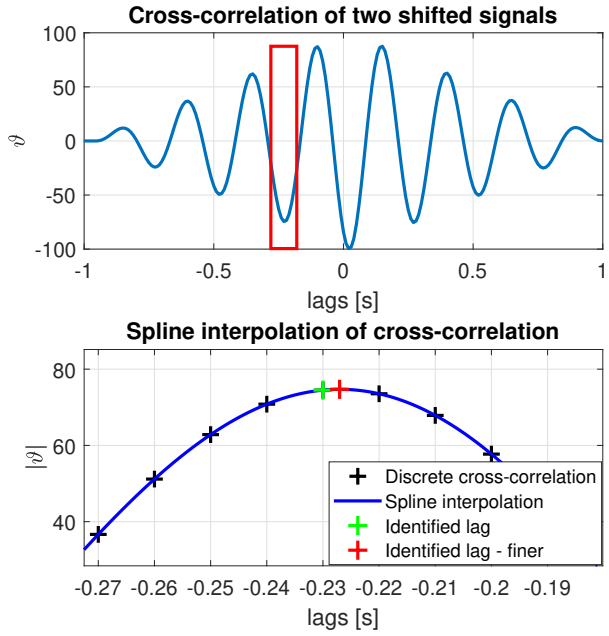

Fig. 3. Cross-correlation of two shifted periodic signals within sliding window $T_W = 1$ s and time-step $\Delta t = 0.01$ s (upper graph) and the detail of estimated range of the total time shift (lower graph).

by finding the maximum of such a spline on the interval $(\tilde{\tau} - \Delta t, \tilde{\tau} + \Delta t)$.

2.3 Disturbance identification

The disturbance is identified when the system runs without control. The approach is similar to the time delay tracking. It is based on tracking small inaccuracies in the initial estimate. In our case, we assume that the disturbance has character according to (2). There are six parameters to identify: ω_1, ω_2, a_1, a_2, ϕ_1, ϕ_2. For the identification of disturbance frequencies ω_1, ω_2 and phase shifts ϕ_1, ϕ_2, the discrete convolution of an adaptive Morlet wavelet and an output signal $\boldsymbol{y}(t)$ is used:

$$\boldsymbol{\Gamma}[n,\omega] = (\boldsymbol{y} * \boldsymbol{\Psi})[n,\omega] = \sum_{k=1}^{N} \boldsymbol{y}[k] \cdot \boldsymbol{\Psi}[n-k,\omega]. \quad (25)$$

Where N is the number of samples in the sliding window and ω is changing in the desired range of frequency identification. The wavelet is a symmetrically damped cosine function:

$$\bar{\boldsymbol{\Psi}}[k,\omega] = \exp\left(\frac{(-k\Delta t)^2}{2\sigma[\omega]^2}\right) \cdot \cos\left(\omega \cdot k\Delta t\right). \quad (26)$$

The damping is proportional to the period of oscillations:

$$\sigma[\omega] = 2 \cdot T_\omega = \frac{4\pi}{\omega}. \quad (27)$$

The resulting wavelet should have a sum equal to 1 for each ω. Thus, every wavelet is divided by its sum:

$$\boldsymbol{\Psi}[k,\omega] = \frac{\bar{\boldsymbol{\Psi}}[k,\omega]}{\sum_{k=1}^{N} \bar{\boldsymbol{\Psi}}[k,\omega]}. \quad (28)$$

The identified frequency is considered that ω, for which the sum of squared convolution $\boldsymbol{\Gamma}[n,\omega]$ (25) is maximized:

$$\tilde{\omega} = \arg\max_{\omega} \sum_{k=1}^{N} \boldsymbol{\Gamma}^2[k,\omega]. \quad (29)$$

The identified time shift is calculated from the position of a peak in convolution for identified $\tilde{\omega}$:

$$\tilde{n} = \arg\max_{n} \boldsymbol{\Gamma}[n,\tilde{\omega}], \quad (30)$$

where the shift in radians is:

$$k \cdot \tilde{\phi} = \left(\tilde{n}\Delta t - \frac{T_{\tilde{\omega}}}{4}\right) \cdot \tilde{\omega},\ k \in \mathbb{Z}. \quad (31)$$

One wavelet can identify one $\tilde{\omega}$ and one $\tilde{\phi}$. Thus, it is necessary to use two wavelets to identify both sine components.

After identification of the frequencies and phase shifts of both sine components, the amplitudes a_1, a_2 are identified using the discretized vector of $\boldsymbol{y}(t)$ and the discretized vector of $\hat{\boldsymbol{d}}(t)$, which is calculated by substituting $\tilde{\omega_1}$, $\tilde{\omega_2}$, $\tilde{\phi_1}$, $\tilde{\phi_2}$ in equation for disturbance (2). The amplitudes a_1 and a_2 are identified by sweeping around the expected values minimizing the sum of squared error between measured signal and the model of disturbance:

$$a_1, a_2 = \arg\min_{a_1,a_2} \sum_{k=1}^{N} \left(\boldsymbol{y}[k] - \hat{\boldsymbol{d}}[k, a_1, a_2, \tilde{\omega_1}, \tilde{\omega_2}, \tilde{\phi_1}, \tilde{\phi_2}]\right)^2. \quad (32)$$

2.4 Algorithm

The simplified algorithm scheme is shown in Fig. 4. To identify the initial disturbance, it is necessary to run the system without control. After identifying the disturbance, the controller is activated and it is possible to track the time shift between the input to the system from the controller $\boldsymbol{u}(t)$ and the output of the system subtracted by the estimated disturbance $\tilde{\boldsymbol{y}}(t) = \boldsymbol{y}(t) - \hat{\boldsymbol{d}}(t)$. If the average output values $\boldsymbol{y(t)}$ in the sliding window T_W are damped below the user-defined limit $\bar{\boldsymbol{y}}(t) < y_{lim}$ and the change in the identified delay $\tilde{\tau}(t)$ is less than the user-defined limit $\Delta\tilde{\tau}(t) < \tau_{lim}$, then the identified delay is held as the maximum value $\tilde{\tau}(t) = max(\bar{\boldsymbol{\tau}}(t))$, where $\bar{\boldsymbol{\tau}}$ is:

$$\bar{\boldsymbol{\tau}}(t) = [\tilde{\tau}(t-((M-1)\Delta t), \tilde{\tau}(t-(M-2)\Delta t), \ldots, \tilde{\tau}(t)] \quad (33)$$

in the sliding window of length:

$$M = \frac{2 \cdot T_\omega}{\Delta t}. \quad (34)$$

We hold the maximum value because the identified $\tilde{\tau}(t)$ oscillates. The oscillations are caused by the mismatch of the length of sliding window and the integer multiple of the disturbance period T_ω.

3. NUMERICAL VALIDATION

The proposed method was simulated in Matlab-Simulink using the ODE45 solver, with max. step size equal to Δt and relative tolerance equal to 10^{-9}. The exact parameters of the system, controller, and adaptive algorithm can be seen in Table 1.

The first five seconds of simulation are without control, as you can see in Fig. 5, then the controller is activated. The evolution of the variable delay is shown in Fig. 6. The delay is equal to the initial estimate at the beginning of the simulation and the controller is able to suppress the disturbance very quickly. The delay changes after 15 seconds of simulation by 10 % with a slope of 0.1, and after 30 seconds it increases by 20 % with the

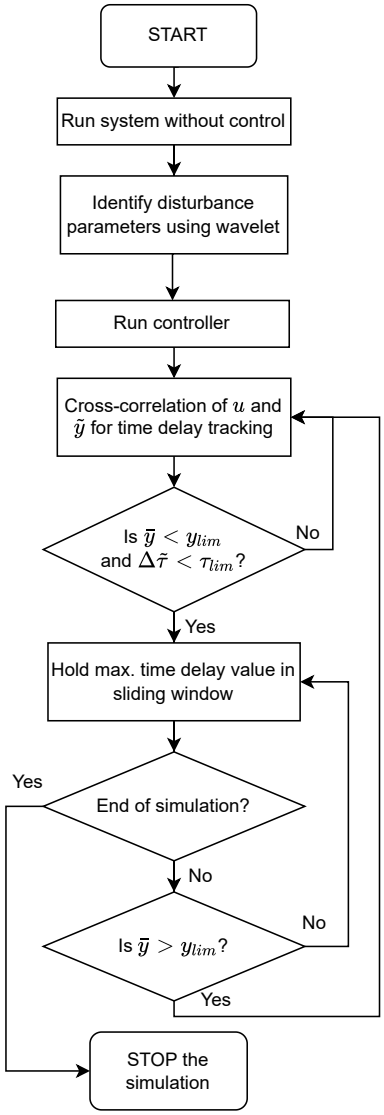

Fig. 4. Simplified algorithm of time delay tracking

Table 1. Parameter values for simulation

Parameter:	**Value:**
$\boldsymbol{p} = [p_1\ p_2\ p_3\ p_4\ p_5]$	[-15 -30 -45 -60 -75]
T [s]	0.017
K [-]	0.587
τ [s]	0.211
Δt [s]	0.01
$\boldsymbol{\omega} = [\omega_1\ \omega_2]$ [rad·s^{-1}]	[8π 16π]
θ [s]	0.039
C [-]	0.2
y_{lim} [mm]	0.05
τ_{lim} [-]	0.005
T_W [s]	5

same slope. The speed of tracking the delay change depends on the length of the sliding window T_W.

The response to the delay change is promising. The oscillations in the case of a 10 % change are less than 1.5 mm, which is much smaller than the disturbance amplitude (3.5 mm), and the

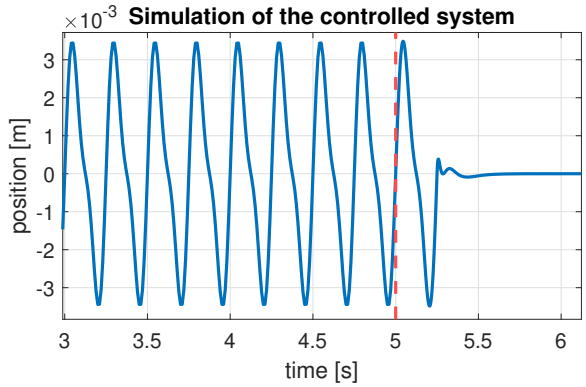

Fig. 5. Simulation without control at the beginning. Control started after 5 seconds.

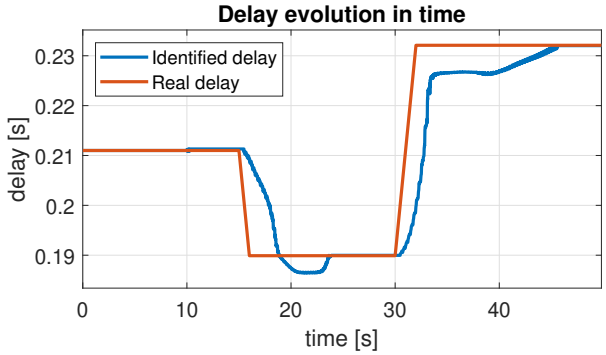

Fig. 6. Time delay evolution in time

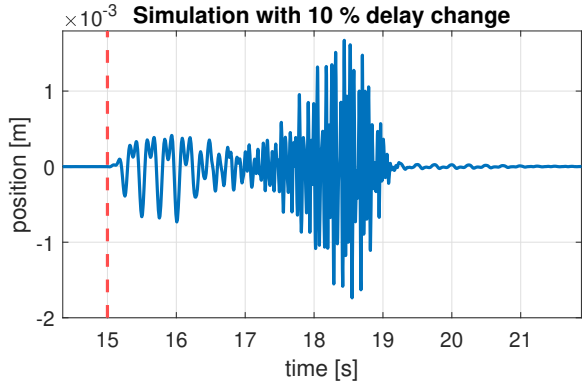

Fig. 7. Response to 10 % delay change after 15 seconds of simulation.

oscillations are damped in less than 5 seconds (Fig. 7). As can be seen in Fig. 8, the oscillations caused by the 20 % change are less than 15 mm, which is more than the original disturbance, but they are also damped quickly in less than 10 seconds.

4. DISCUSSION

The simulation in Matlab-Simulink provides promising results, but there are few points for further discussion. In this case, we simulated only a variable time delay, and the adaptive wavelet was used only for initial disturbance identification. The disturbance features are considered constant and without any other noise. Our approach needs the update of the disturbance parameters, because even for small inaccuracies of disturbance identification, the time delay tracking can fail in a long time

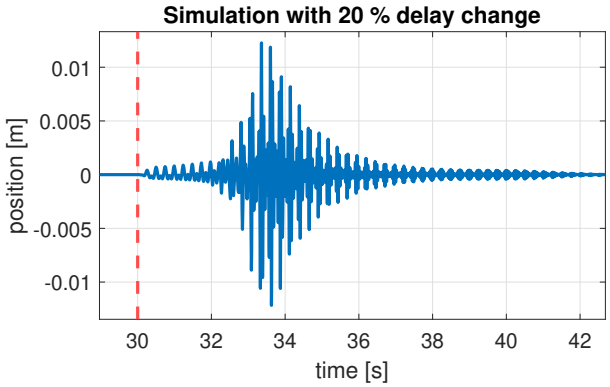

Fig. 8. Response to 20 % delay change after 30 seconds of simulation.

frame. Another problem can occur in case the frequencies of the disturbance are close to each other. Then it would be necessary to pay attention to Butterworth filter design. This method cannot deal with disturbance and time delay identification at the same time. Another problem is the separation of the impact of the system time constant T, which is considered known and constant. Time delay tracking would fail if the delay change is greater than the base period T_ω, because the algorithm would track a different position of the peak in cross-correlation. However, the main purpose of the application of this algorithm is to handle small and slow changes in time delay because even small changes can lead to instability.

5. CONCLUSION

An adaptive IMC controller design to suppress two-harmonic disturbances acting on a first-order system with dead-time has been proposed and numerically validated. The proposed filter structure for the IMC controller explicitly distinguishes the controller parameters responsible for delay compensation and disturbance rejection, allowing fast adaptation of the controller parameters for a newly identified system delay.

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