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Designing a Fuzzy Controller Based on Disturbance Observer and Smith Predictor for Linear Uncertain Time-Delay Systems

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ABSTRACT

In control systems, conventional disturbance observer (DOB) structures often fail to perform optimally when the system involves delays, leading to inefficiencies in disturbance rejection. This paper addresses this limitation by first employing the conventional Smith predictor method to compensate for the negative effects of delay within the control loop. Following this, a conventional disturbance observer is implemented to estimate external disturbances. However, this approach has certain constraints, particularly in handling unpredictable or complex disturbances. To overcome these challenges, this study explores an alternative approach: the Composite Disturbance Observer (CDOB), which is based on the concept of Network Disturbance (ND). In this framework, system delay is treated as an external disturbance, and since the transformed system becomes delay-free, the conventional DOB structure can be applied effectively. A key advantage of the proposed CDOB method is its ability to estimate and compensate for disturbances without requiring prior knowledge of the delay or assuming specific conditions such as periodic disturbances, which are often considered in related studies. Furthermore, a fuzzy PID controller is utilized for process control, offering adaptive tuning capabilities to enhance performance. The proposed approach is validated through comprehensive simulations, which demonstrate the superior performance of the CDOB in mitigating the adverse effects of delay while ensuring robust disturbance rejection. The results highlight the effectiveness of this method in improving system stability and response under various operating conditions.

1. INTRODUCTION

Control systems in the industry are consistently exposed to disturbances. External disturbances and uncertainties adversely affect the performance and stability of control systems [1-5]. Thus, disturbance elimination in control systems is crucial and receives significant attention. Robust control methods are effective in mitigating the impact of disturbances on the output. This issue is more critical for time-delay systems, as delay itself negatively impacts

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system stability. One approach to disturbance compensation is using a disturbance observer. Disturbance observers are extensively used in missile systems and vibration control.

The conventional disturbance observer structure in the frequency domain employs a low-pass filter to mitigate disturbances [6]. This structure is inefficient for time-delay systems. The generalized structure, which improves the low-pass filter and makes minor modifications to the conventional structure, provides better results [7]. One of the drawbacks of this method is limiting the disturbance to periodic disturbances. This approach can consider system uncertainties as external disturbances and estimate the set of external disturbances along with uncertainties using the proposed structure. Designing the Q filter in the generalized structure is of particular importance. The cutoff frequency of the filter has a direct impact on the robust performance of the system. Additionally, in the time domain, and for delay in the steady state, methods for disturbance estimation have been proposed using the Lyapunov-Krasovskii functional to reach a matrix inequality, which, when solved, yields the controller and observer gains. The drawback of this method is limiting the disturbance to sinusoidal disturbances [8].

Besides the disturbance observer, other methods exist for eliminating external disturbances. The extended Smith predictor structure [9] and the extended Smith-Storm predictor structure are among the methods used for disturbance estimation and compensation. The combination of the extended Smith predictor structure with the predictive controller for eliminating periodic disturbances has also been discussed. Using the extended Smith predictor structure alone is effective for disturbance elimination [11]. This method is also used for unstable systems; however, the necessity of having four controllers in this structure increases the complexity of the control system. The combination of the Smith predictor structure and the disturbance observer is an idea examined in this paper. In this method, the conventional Smith predictor is used to compensate for delay, and the disturbance observer is used to compensate for external disturbances.

The CDOB method, based on the ND idea, is also examined and simulated in this paper. In this method, the delay is considered an external disturbance [13, 14, 15]. The advantage of this method is that there is no necessity for periodic disturbances, and uncertainties can be added to the set of external disturbances, ultimately estimating the set of disturbances with the conventional structure. In this paper, a fuzzy controller is used to control the system, and the control signals include the output signal from the controller and the disturbance estimate. Therefore, the control signal is based on disturbance estimation . $u_c = u_{fuzzy} - \hat{d}$

2. PROBLEM DEFINITION

External disturbances adversely affect the performance and stability of control systems. Therefore, the estimation and mitigation of disturbances are of significant importance. In systems that also involve delays, the issue of disturbance rejection becomes even more critical.

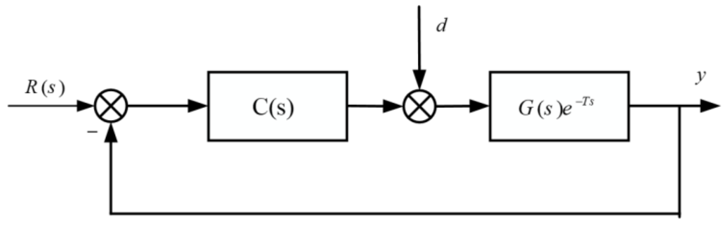


Fig. 1. Block diagram of a delayed system with external disturbance

By deriving the transfer function from input to output in the above block diagram:

$$\frac{Y(s)}{R(s)} = \frac{C(s)G(s)e^{-Ts}}{1 + C(s)G(s)e^{-Ts}}$$
$$\Delta(s) = 1 + C(s)G(s)e^{-Ts} \quad (1)$$

The presence of delay in the characteristic equation can lead to the instability of the closed-loop system. In such cases, the conventional disturbance observer (DOB) is ineffective. This article proposes two methods to compensate for the delay. In the first method, a Smith predictor is used to eliminate the adverse effects of delay on the inner loop. In the second method, the ND (Newton Divided) difference concept is employed, considering the delay as an external disturbance. Ultimately, these two methods make the use of the conventional disturbance observer feasible.

2.1. Conventional Disturbance Observer in the Frequency Domain

Consider the following single-input single-output (SISO) minimum phase system [6]:

$$y(s) = G_p(s)[u(s) + d(s)] \tag{2}$$

where D(s) represents the disturbance entering the system, and U(s) is the control input. The typical structure for a disturbance observer is as follows, where Gn is the nominal system, and Q(s) is a low-pass filter. The frequency range of the disturbance is considered to be $0 < \omega < a$, where the upper bound a is a small constant.

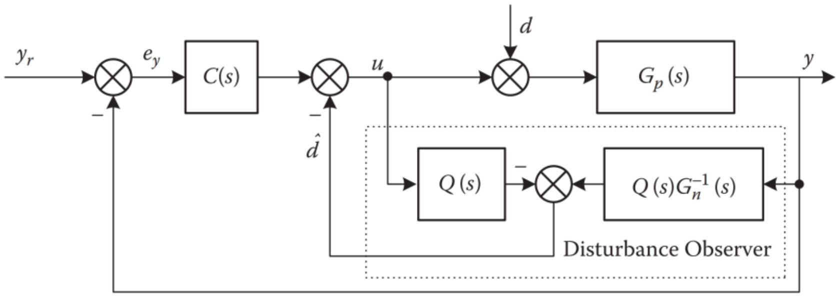


Fig. 2. Conventional Disturbance Observer Structure

The output of the system can be expressed as follows [6]:

$$Y(s) = T_{yr}(s)Y_r(s) + T_{yd}(s)D(s)$$

where:

$$T_{ry}(s) = \frac{G_n(s)G_p(s)C(s)}{G_n(s)[1 + C(s)G_p(s)] + Q(s)[G_p(s) - G_n(s)]} \tag{3}$$

$$T_{dy}(s) = \frac{G_n(s)G_p(s)[1 - Q(s)]}{G_n(s)[1 + C(s)G_p(s)] + Q(s)[G_p(s) - G_n(s)]} \tag{4}$$

To reduce the impact of the disturbance on the output, the design of the filter Q is of particular importance. In other words, according to equation (4), if the filter Q is designed as a low-pass filter ($\lim_{\omega\to 0} Q(j\omega) = 1$)we will have:

$$\lim_{\omega\to 0} T_{ry}(j\omega) = \lim_{\omega\to 0} \frac{G_n(j\omega)C(j\omega)}{1 + G_n(j\omega)C(j\omega)}$$

$$\lim_{\omega\to 0} T_{dy}(j\omega) = 0 \tag{5}$$

Therefore, considering the frequency range of the disturbance, its effect on the output can be eliminated.

2.2. Smith Predictor [11, 12]

The Smith predictor is widely used in delayed systems. It compensates for the adverse effects of delay in the closed-loop system. The main idea of the Smith predictor is to remove the delay from the control loop. If it is necessary to eliminate the effect of delay on the control loop, the following block diagrams should be equivalent:

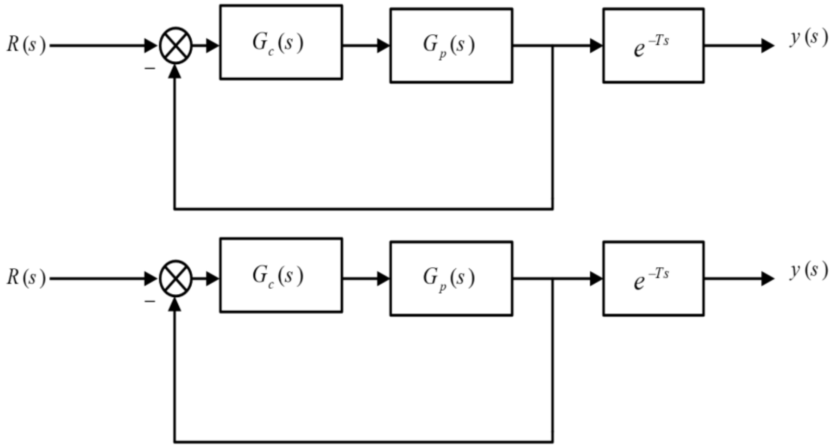


Fig. 3. Closed-loop System with Delay

Given the equivalence of the above block diagrams, $C^*(s)$ is calculated as follows:

$$\frac{C^*(s)G_p(s)e^{-Ts}}{1+C^*(s)G_p(s)e^{-Ts}} = \frac{G_c(s)G_p(s)e^{-Ts}}{1+C^*(s)G_p(s)}$$

$$C^*(s) = \frac{G_c(s)}{1+G_c(s)G_p(s)(1-e^{-Ts})} \quad (6)$$

Thus, the structure of the Smith predictor can be represented as follows:

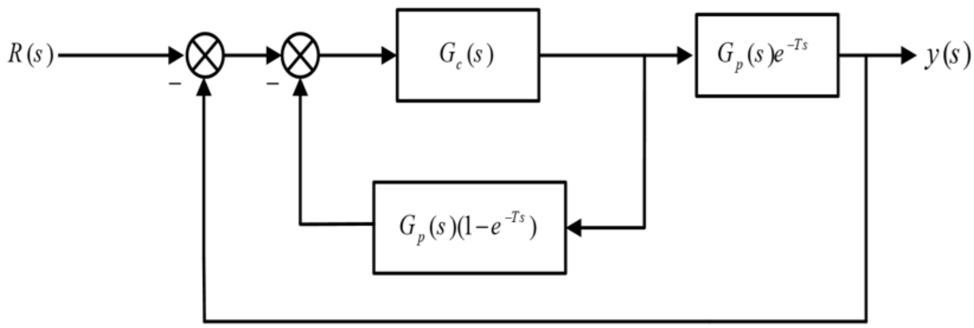


Fig. 4. Conventional Smith Predictor

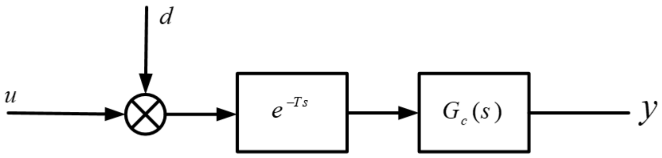
The transfer function from the reference input to the output is:

$$\frac{y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-Ts}}{1 + G_c(s)G_p(s)} \quad (7)$$

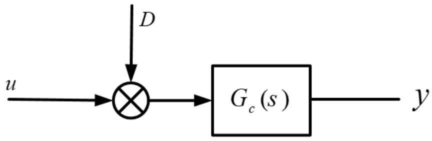
T(s) = \frac{G_n(s)}{1 + C(s)G_n(s)}

2.3. Considering Delay as a Disturbance [13, 14, 15]

Consider the following linear minimum phase delayed system [11]:



where $G_p(s) = e^{-Ts}G_c(s)$Now, if the delay is considered as an external disturbance, we have:



(8)

Since the delay is considered as a disturbance, the block diagrams 7 and 8 are equivalent, resulting in:

$$(u + D)G_c = y$$

$$(u + d)e^{-Ts}G_c(s) = y \tag{9}$$

By equating the two relationships above:

$$(u + d)e^{-Ts} = u + D \Rightarrow D = (u + d)e^{-Ts} - u$$

Given the above details, the conventional structure can be used. Additionally, considering block diagram 4, uncertainties can also be treated as disturbances.

$$D_{net} = (u + D)e^{-Ts} - u + D_m \tag{10}$$

3. DESIGNS

3.1. Design of Disturbance Observer Based on Smith Predictor

By compensating for the delay using the Smith predictor, the conventional disturbance observer structure and the Smith predictor can be combined to accurately estimate external disturbances. Evidently, in this method, uncertainties can be considered as part of the disturbance. The block diagram below illustrates this structure:

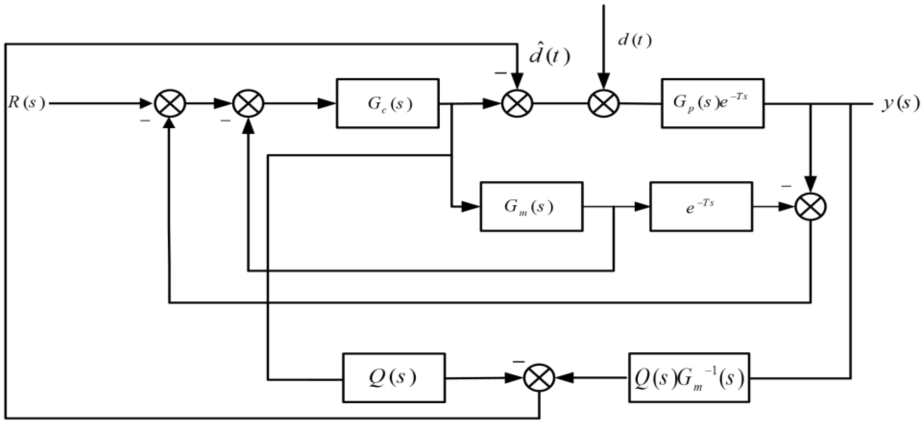


Fig. 5. Disturbance Observer and Smith Predictor

3.2. Design of Disturbance Observer Based on ND Method

In the CDOB method, which is based on the ND approach, delay and uncertainty were considered as external disturbances, and the overall disturbance was termed as the network disturbance. By combining this method with the structure of a conventional disturbance observer, one can achieve estimation and compensation of the network disturbance.

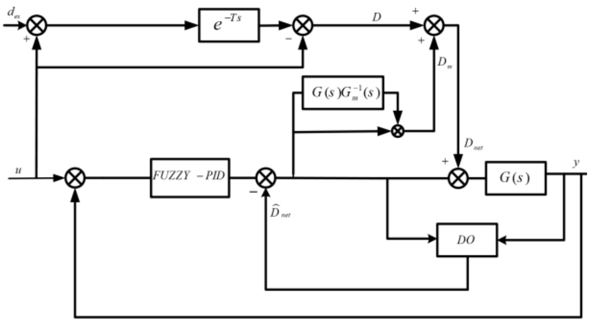


Fig. 6. Conventional Disturbance Observer and ND

3.3. Fuzzy PID Controller [16, 17]

A PID controller in general form can be expressed as:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \qquad (11)$$

where:

$$K_i = \frac{K_p}{T_i}, K_d = K_p T \qquad (12)$$

The PID coefficients can be obtained using the Ziegler-Nichols method. Instead of using the coefficientsK_d, K_i, K_d, one can consider the coefficients $K_p, K_d,\ \alpha$, where:

$$\alpha = \frac{T_i}{T_d}, K_i = \frac{K_p^2}{\alpha K_d} \qquad (13)$$

Furthermore, to normalize the coefficients, we have:

$$K_p{}' = \frac{K_p - K_p^{min}}{K_p^{max_p^{min}} \in [0,1]}$$

(14)

$$K_d{}' = \frac{K_d - K_d^{min}}{K_d^{max_d^{min}} \in [0,1]}$$

Based on the approach presented in the references, and by defining appropriate membership functions and fuzzy rules, the following structure is implemented for the fuzzy controller. Additionally, the coefficients K_d, K_i, K_d can be calculated using the coefficients $\alpha, K_p{}', K_d{}'$.

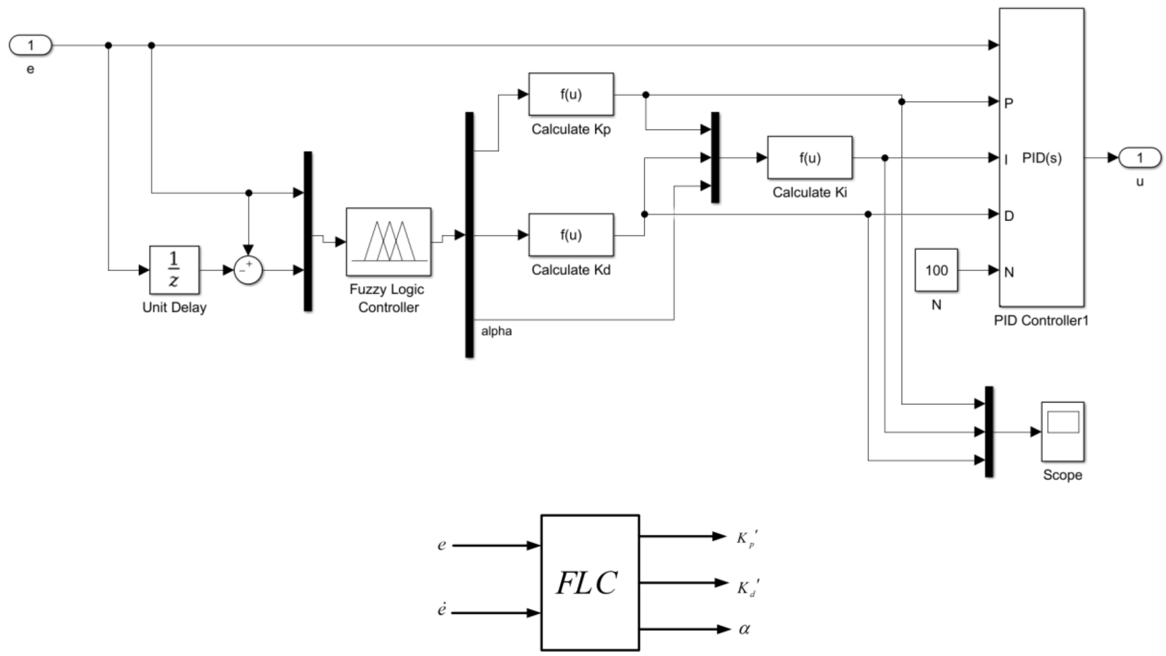


Fig. 7. Implementation of Fuzzy Controller

The following tables show the fuzzy rules for the coefficients k_p' و k_d' and α:

Table 1. Fuzzy rules for k_p'

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZO	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

Table 2. Fuzzy rules for $k_d^{'}$

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	S	S	S	S	S	S	S
	NM	B	B	S	S	S	B	B
	NS	B	B	B	S	B	B	B
	ZO	B	B	B	B	B	B	B
	PS	B	B	B	S	B	B	B
	PM	B	B	S	S	S	B	B
	PB	S	S	S	S	S	S	S

Table 3. Fuzzy rules for α

		$\Delta e(k)$						
		NB	NM	NS	ZO	PS	PM	PB
$e(k)$	NB	2	2	2	2	2	2	2
	NM	3	3	2	2	2	3	3
	NS	4	3	3	2	3	3	4
	ZO	5	4	3	3	3	4	5
	PS	4	3	3	2	3	3	4
	PM	3	3	2	2	2	3	3
	PB	2	2	2	2	2	2	2

4. SIMULATION

Consider the following linear, third-order, and time-delayed nominal system:

$$G(s) = \frac{e^{-0.2s}}{(s+1)(s+2)(s+3)}$$

which with uncertainty becomes:

$$G_m(s) = \frac{e^{-0.2s}}{(s+1+\alpha)(s+2+\beta)(s+3+\gamma)} \qquad -3 \le \alpha, \beta, \gamma \le 3$$

Assuming that the following disturbance is applied to the above system:

$$d(t) = 0.2\, sin(\, 0.4t + 30) u(t-20)$$

The estimation of the disturbance and the network disturbance, as well as the system output, are simulated:

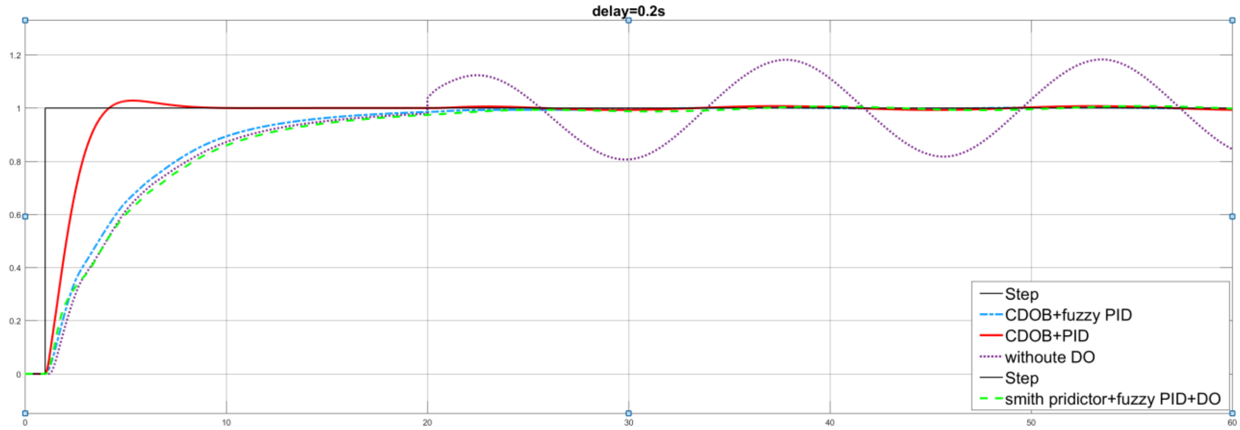


Fig. 8. Step response in the presence of disturbance

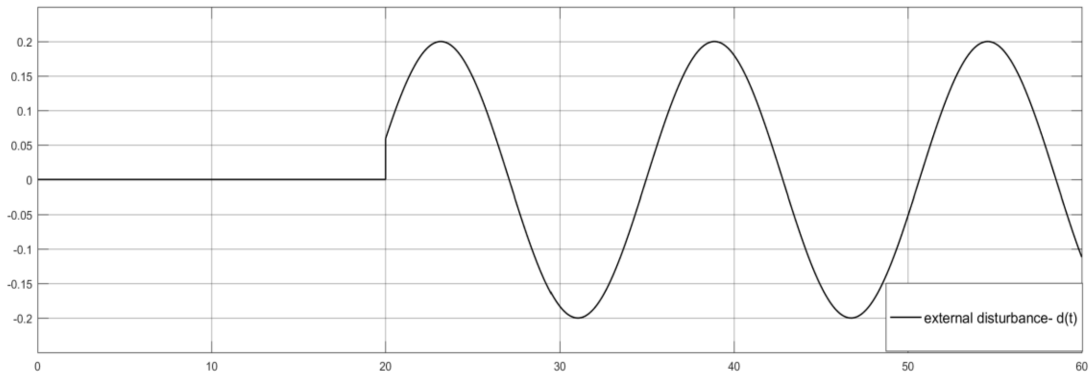


Fig. 9. External disturbance d(t)

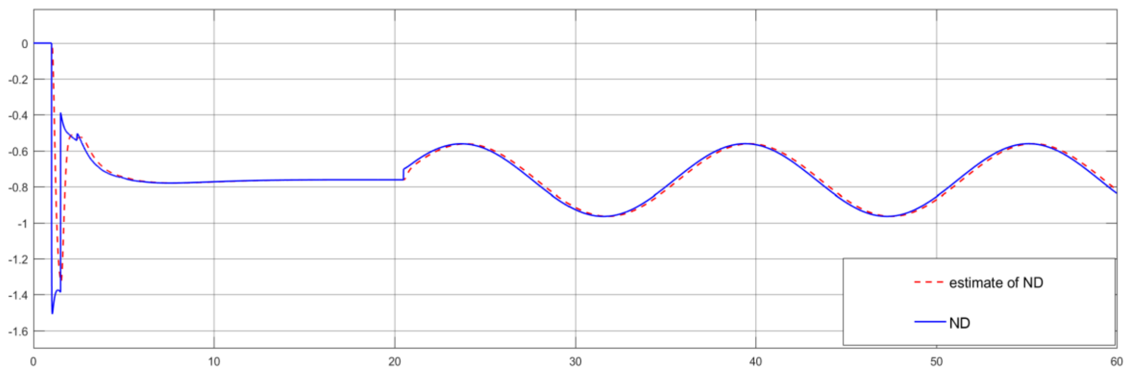


Fig.10. Network disturbance and its estimation

Now, let's examine the response in the presence of the following disturbance:

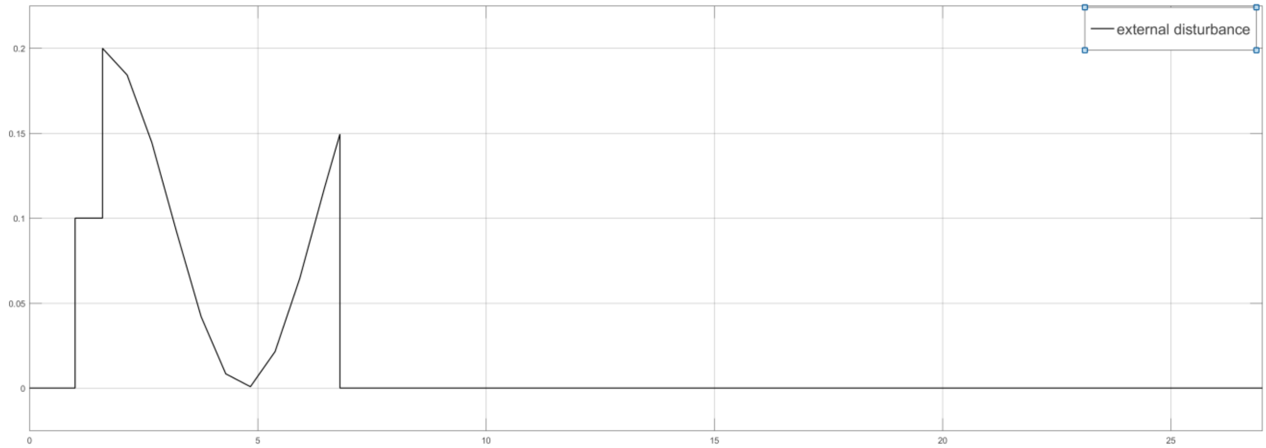


Fig. 11. External disturbance

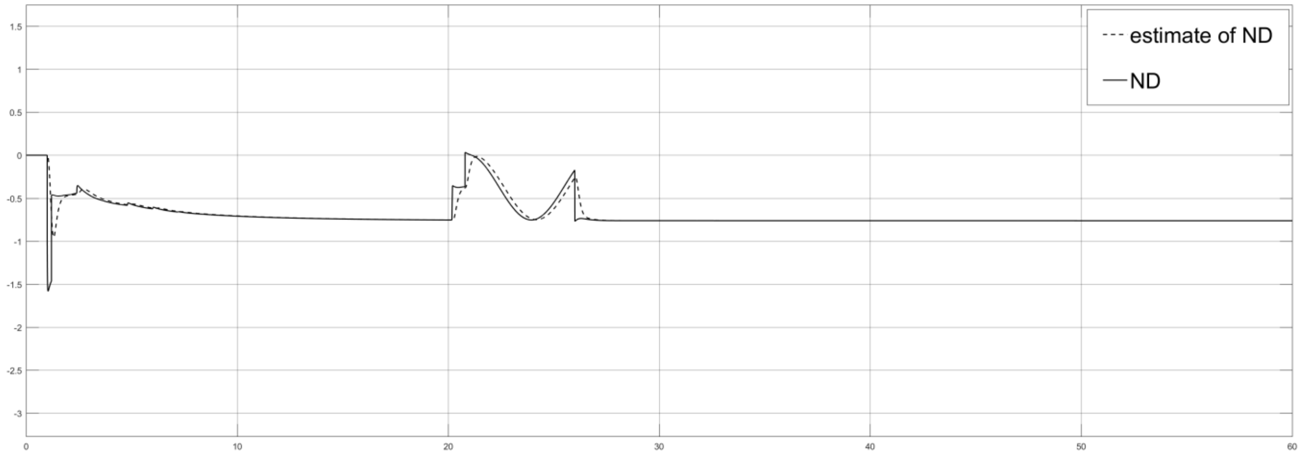


Fig. 12. Network disturbance and its estimation

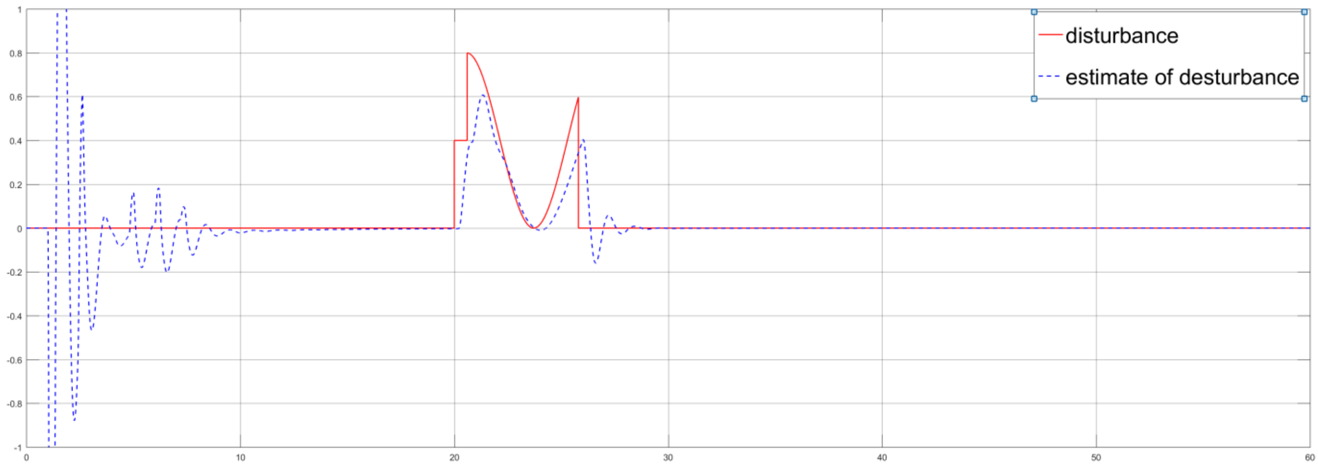


Fig. 13. External disturbance and its estimation (Smith method)

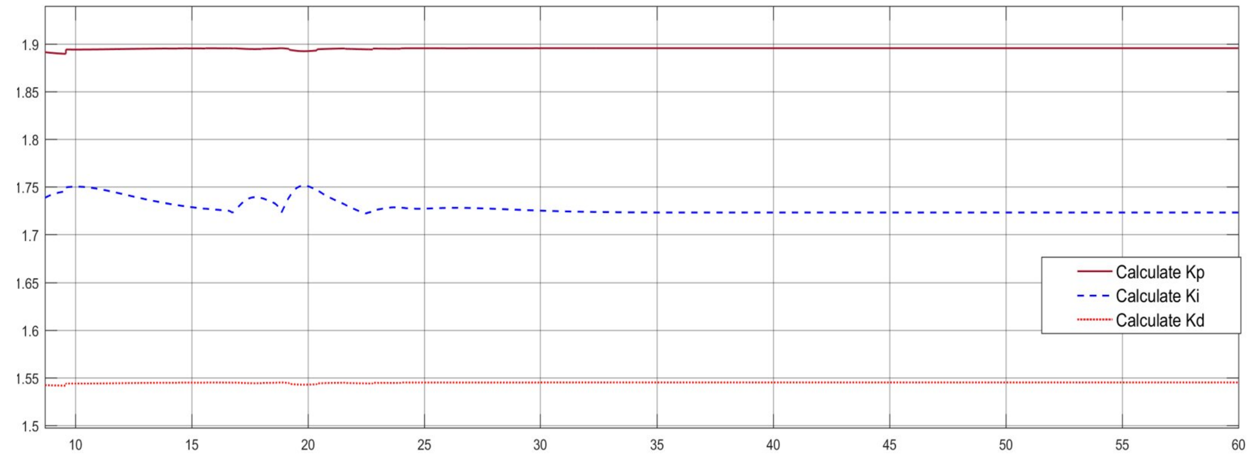


Fig. 14. PID coefficients

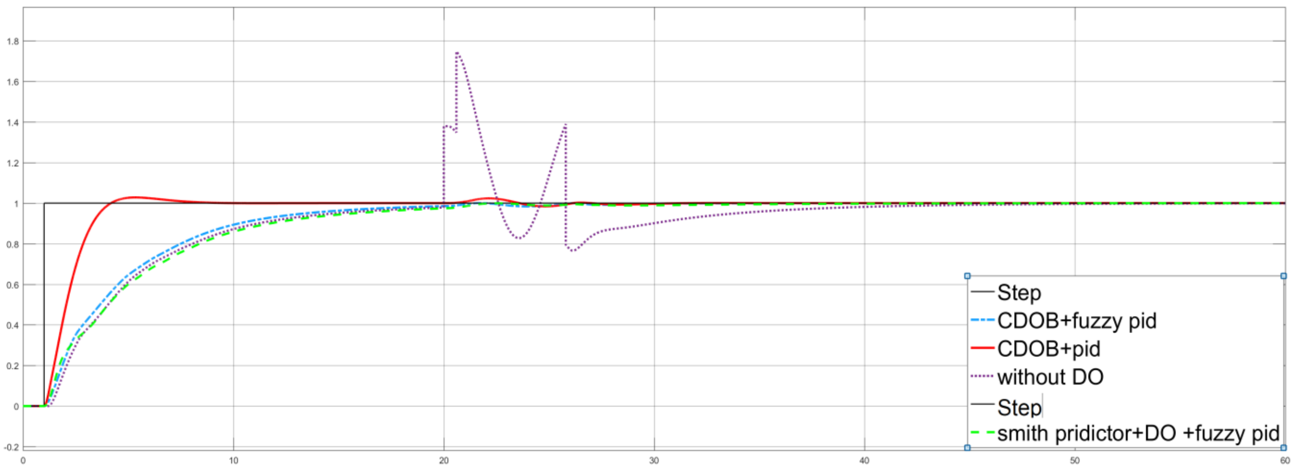


Fig. 15. Step response

5. CONCLUSION

The CDOB method does not limit external disturbances to a particular type and does not impose any specific conditions on external disturbances. In this method, delay does not appear as a detrimental factor in the output, so it can be used for delay-based systems that are not subject to disturbances, and the adverse effect of delay can also be compensated.

The use of a fuzzy controller results in a reduction in the overshoot of the response compared to the case where a conventional PID controller is used. However, the response speed is reduced, and the settling time is increased. Depending on the type of system, each controller can be suitable. For example, in cases where overshoot is considered undesirable and response speed is not critical, the use of a fuzzy controller is more appropriate. In the simulation example, a disturbance was applied to the system with a time delay of 0.2 seconds at t=20s. The use of the fuzzy controller has exhibited a more robust performance. The following figure clearly illustrates this in the presence of the disturbance.

$$d(t) = 1\,sin(\,0.4t + 30)u(t - 20)$$

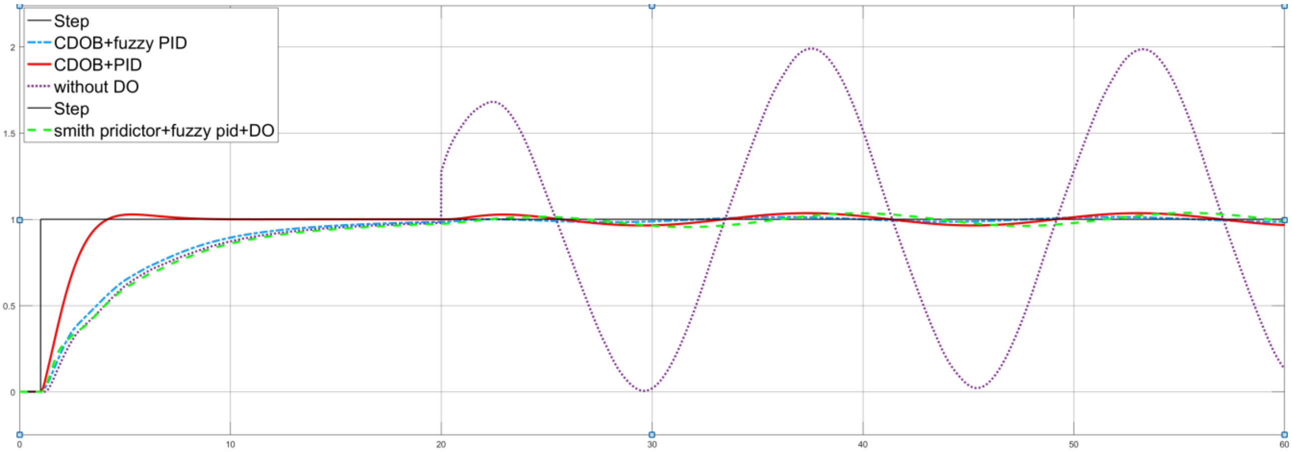


Fig. 16. Step Response

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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