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DISTURBANCE REJECTION CONTROL FOR COAGULANT DOSAGE IN WATER TREATMENT PROCESS

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Abstract. *Coagulation is one of the most important steps in drinking water treatment. Determining the optimal coagulant dosage is vital to stabilize the quality of the treated water and improve the efficiency of coagulation. However, strong external disturbances always exist, including changes in raw water quality and water flow rate. Moreover, the coagulation process is a nonlinear system with long time delay and large inertia. It is not easy to make the turbidity of the treated water constant due to these strong disturbances. Several control strategies have been proposed to control the coagulation process. However, most of them (such as PID (proportional-integral-derivative) and MPC (model predictive control)) reject disturbances merely through feedback regulation and do not deal with the disturbances directly, which may lead to poor control performance when strong disturbances occur. To improve disturbance rejection performance, a control scheme based on PID and disturbance observer (DOB) is put forward in this paper. The scheme combines a feedforward compensation based on disturbance observer and a feedback regulation using PID. The test results illustrate that the proposed method can obtain remarkable superiority in disturbance rejection compared with PID method in the coagulation process.*

Keywords: Disturbance observer, PID-DOB, Disturbance rejection, Coagulant dosage

1. Introduction.

In the water treatment, coagulation is an important process, which can reduce the turbidity of raw water by adding the coagulant. In the coagulation process, it is vital to determine the optimal coagulant dosage. Doses that are not sufficient will cause unsatisfying treated water quality. On the other side, too high doses will lead to high cost and health problems [1]. In general, the control strategy for coagulant dosage is to maintain the turbidity of the treated water constant [2]. Operators try to maintain the turbidity of the treated water at the setpoint by manually adjusting the coagulant dosage. However, besides the coagulant dosage, the raw water quality (pH, temperture, especially turbidity) and the water flow rate will also greatly affect the turbidity of the treated water [3]. Moreover, the raw water quality and the water flow rate will vary in the process and these variations are hard to express with an accurate mathematical model [1]. In addition, the coagulation process consists of many long-time chemical and physical reactions [4]. In this case, undesirable characteristics, such as long time delay, large inertia, nonlinear and strong disturbances exist when controlling the turbidity of the treated water. It is a challenge to control the turbidity of the treated water constant under the changeable and usually unpredictable raw water quality and water flow rate.

To solve this problem, a widely used method is to use a PLC (programmable logic controller), dosing pump and turbidity meter to form a feedback control loop. The classical PID control algorithm [5] and some more advanced control algorithms are proposed and employed, including fuzzy logic algorithm [4], neural network [6], model-predictive control

[7], and so on. Note that, complexity of tuning sometimes lowers the attractiveness of the advanced methods comparing with the well-known and industrially-proven PID algorithm controller.

In the coagulation process, various disturbances, including external ones and internal ones (model mismatch), exist in the control system. Note that, the above-mentioned advanced control principles can only reject disturbances by the feedback regulation. Considering the disturbances in this coagulation process are difficult to measure or forecast, a feedforward compensation based on disturbance observer (DOB) is introduced to improve the control performance [8]. DOB is an effective technique to estimate disturbances and widely applied in various practical systems [8,9].

In this work, a DOB-PID scheme is proposed to improve the disturbance rejection performance of the coagulation process. The scheme combines a feedforward compensation based on DOB with a feedback regulation using PID. This paper is organized as follows. In Section 2, the coagulation process is briefly described. Then the DOB-PID control scheme is proposed in Section 3. In Section 4, the disturbance rejection performances are strictly analyzed and discussed. Finally, the conclusions are summarized.

2. **Process Description.**

In the coagulation process, coagulation/flocculation, sedimentation and filtration are commonly used treatment steps [1]. Figure 1 illustrates a typical simplified coagulation system. In flocculation basin, the coagulants (such as PAC) are added to destabilize particles in raw water by neutralising their surface charge. Then the destabilised particles aggregate to form particles that are large enough to settle out of water in the sedimentation process. Filtration is the last step of the clarifying process, in which physical barriers are used to screen out the aggregated particles [1].

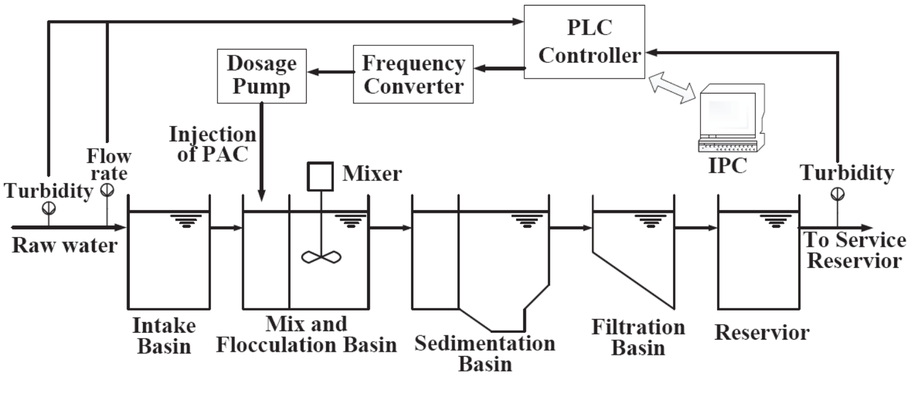


Figure 1. Schematic diagram of a coagulation process

In the coagulation control system, the turbidity of the treated water y(NTU) is the most important controlled variable, which needs to be kept at a desired setpoint. Larger or smaller turbidity of the treated water than the setpoint will influence the treated water quality and degrade the production efficiency. The frequency of the frequency converter x(Hz), controlled by the PLC controller, is the manipulated variable. The frequency converter can regulate the rotating speed of the dosage pump to determine the coagulant dosage. However, strong external disturbances, such as changes in raw water quality (mainly the turbidity d_t) and water flow rate d_f, always exist. They will cause the fluctuations of the turbidity of the treated water.

3. **Control Scheme Based on PID and Disturbance Observer.**

In this section, a composite control scheme is proposed to control the turbidity of the treated water. It enhances the performance of the classical PID feedback controller by adding a disturbance observer, which reconstructs and rejects the unwanted perturbation, including the modelling discrepancies and the external disturbances.

The coagulation consists of long-time chemical and physical reactions. It is a long time delay, large inertia and nonlinear process. As shown in [10,11], this dynamic can be modeled as a first-order plus dead-time (FOPDT) form, which is a most commonly used model to describe the industrial process. The transfer function can be represented as

$$G_p(s) = \frac{K_1}{T_1 s + 1} e^{-\theta s}, \tag{1}$$

where K_1 is the transfer factor from frequency to the turbidity of the treated water, T_1 is the time constant, and θ is the time delay.

The coagulation control system can be considered using the following model

$$Y(s) = G_p(s)X(s) + D_{ex}(s), \tag{2}$$

where

$$G_p(s) = g(s)e^{-\theta s}, \tag{3}$$

$$D_{ex}(s) = \sum_{i=1}^{m} G_{di}(s)D_i(s). \tag{4}$$

In Equations (2)-(4), $X(s)$ is the manipulated variable; $Y(s)$ is the controlled variable; $D_{ex}(s)$ shows the effects of external disturbances on $Y(s)$; $D_i(s)$ $(i = 1, 2, \cdots, m)$ is the ith external disturbances. $G_p(s)$ is the model of the process channel. $g(s)$ is the minimum-phase part of $G_p(s)$. $G_{di}(s)$ $(i = 1, 2, \cdots, m)$ is the model of the ith disturbance channel. The nominal model $G_n(s)$ can also be represented as a product of a minimum-phase part $g_n(s)$ and a dead-time part $e^{-\theta_n s}$.

$$G_n(s) = g_n(s)e^{-\theta_n s}. \tag{5}$$

3.1. **Disturbance observer-enhanced PID algorithm.** In this paper, a composite control scheme is proposed. The block diagram is presented in Figure 2.

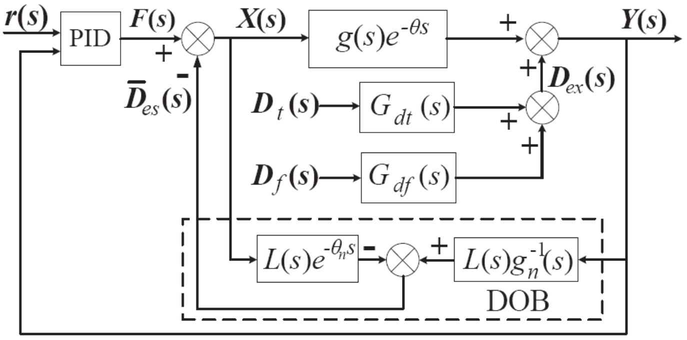


FIGURE 2. Block diagram of the disturbance observer-enhanced PID control

In this figure, $r(s)$ denotes the reference of controlled variable. $F(s)$ represents the output of the PID controller. $\bar{D}_{es}(s)$ is the disturbance estimation. The output is

$$Y(s) = G_c(s)F(s) + G_d(s)D_{ex}(s), \tag{6}$$

with

$$G_c(s) = \frac{g(s)e^{-\theta s}}{1 + L(s)g_n^{-1}(s)\left[g(s)e^{-\theta s} - g_n(s)e^{-\theta_n s}\right]}, \tag{7}$$

$$G_d(s) = \frac{1 - L(s)e^{-\theta_n s}}{1 + L(s)g_n^{-1}(s)\left[g(s)e^{-\theta s} - g_n(s)e^{-\theta_n s}\right]}. \tag{8}$$

From Equations (6)-(8), the performance of disturbance rejection mainly depends on the design of filter $L(s)$. As shown in [9], $\lim_{w\to 0} G_d(jw) = 0$ when $L(s)$ is selected as a low-pass filter with a steady-state gain of 1, i.e., $\lim_{w\to 0} L(jw) = 1$. It means that low-frequency disturbances can be attenuated asymptotically. In this work, $L(s)$ is selected as a first-order low-pass filter with a steady-state gain of 1, which can be represented as

$$L(s) = \frac{1}{\rho s + 1}, \quad \rho > 0. \tag{9}$$

3.2. **Control implementation.** In this work, the proposed control scheme focuses on disturbance rejection against external disturbances as well as model mismatches. The detailed control structure is shown in Figure 3.

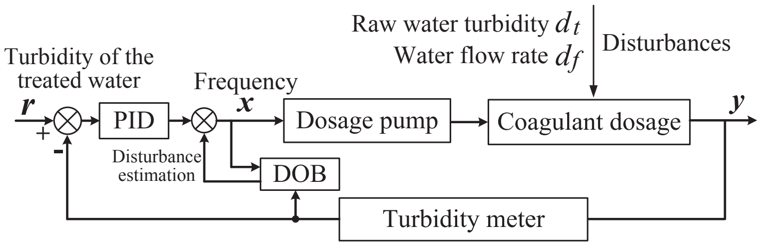


Figure 3. Control structure of constant turbidity of the treated water

From Figure 3, the coagulant dosage directly affects the turbidity of the treated water. For control study, step response of coagulant dosage [10,11] in a pilot-scale facility is tested to develop the transfer function model as follows

$$G_n(s) = \frac{-1.85}{2580s + 1} e^{-900s}. \tag{10}$$

The nominal value is: the turbidity of the treated water, 6.0 NTU. The external disturbances are imposed on the process through disturbance channels. It is known that the raw water turbidity and water flow rate have great influences on the turbidity of the treated water [12,13]. These dynamics can be also modeled as a first-order plus dead-time (FOPDT) form [10,11]. The transfer functions of disturbance channels $G_{dt}(s)$ and $G_{df}(s)$ are also obtained by step response tests and expressed as follows

$$G_{dt}(s) = \frac{7.2}{2340s + 1} e^{-840s}, \tag{11}$$

$$G_{df}(s) = \frac{10.1}{3000s + 1} e^{-790s}. \tag{12}$$

The time constants are expressed in seconds here. Here the disturbances are expressed in a relative change form rather than a real physical unit form. For example, $d_t = 10\%$ means the raw water turbidity has an increase of 10% compared with its nominal value.

Moreover, based on the above discussions, the filter of DOB is employed as

$$L(s) = \frac{1}{0.3s + 1}. \tag{13}$$

The PID controller parameters are designed as

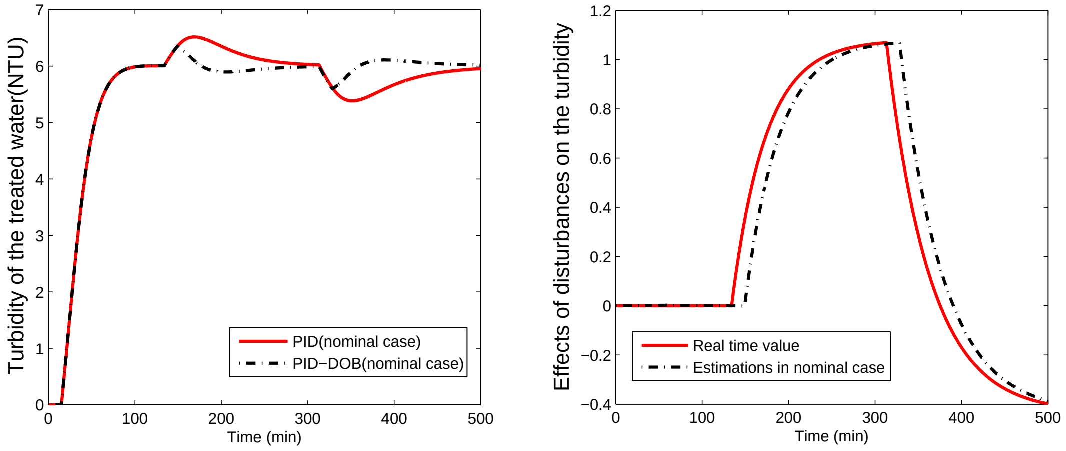
$$K_p = -0.62, \quad K_I = -0.0144. \tag{14}$$

4. **Performance Analysis and Comparisons.** In this part, some results are shown to demonstrate the benefits and practicality of the proposed method. The baseline PID controller is employed for the comparison and the disturbance rejection performance is studied in the nominal case as well as the model mismatch case.

4.1. **Disturbance rejection in nominal case.** Firstly, the nominal case is considered. It means that $G_n(s) = G_p(s)$ holds.

Nominal case: the raw water turbidity has an increase of 15% at $t = 120$min, while the water flow rate has a decrease of 15% at $t = 300$min.

Figure 4(a) shows the response curves of the turbidity of the treated water under the control of DOB-PID and PID. Figure 4(b) gives the effects of external disturbances and the estimations on the controlled variables. From Figure 4(a), it is clear that the dynamic performance under the proposed method is much better than those under the PID method. Compared with the PID method, the proposed method can obtain smaller amplitudes of fluctuations and shorter settling times. From Figure 4(b), the errors between the estimated and real external disturbances are very small, which means that the disturbance observer can effectively estimate the effects caused by disturbances.



(a) (b)

FIGURE 4. Response curves under the two methods in the nominal case: (a) controlled variable, (b) disturbances and their estimations

In order to quantitatively analyze the disturbance rejection performance, two performance indexes including peak overshoot and integral of absolute error (IAE) are employed, which are shown in Table 1. From Table 1, both the overshoot and the IAE value under the proposed method are much smaller than those under the PID method.

TABLE 1. Performance indexes in the nominal case

	Turbidity of the treated water (PID)	Turbidity of the treated water (PID-DOB)
Overshoot (%)	10.3%	6.2%
IAE	350.3	120.1

4.2. **Disturbance rejection in model mismatch case.** In real practice, besides external disturbances, internal disturbances caused by model mismatches are another important factors which affect the control performance of the closed-loop system. The DOB method can reject not only external disturbances, but also the internal disturbances caused by model mismatches [9]. In this part, some simulation studies are done to demonstrate the lumped disturbance rejection performance of the proposed method.

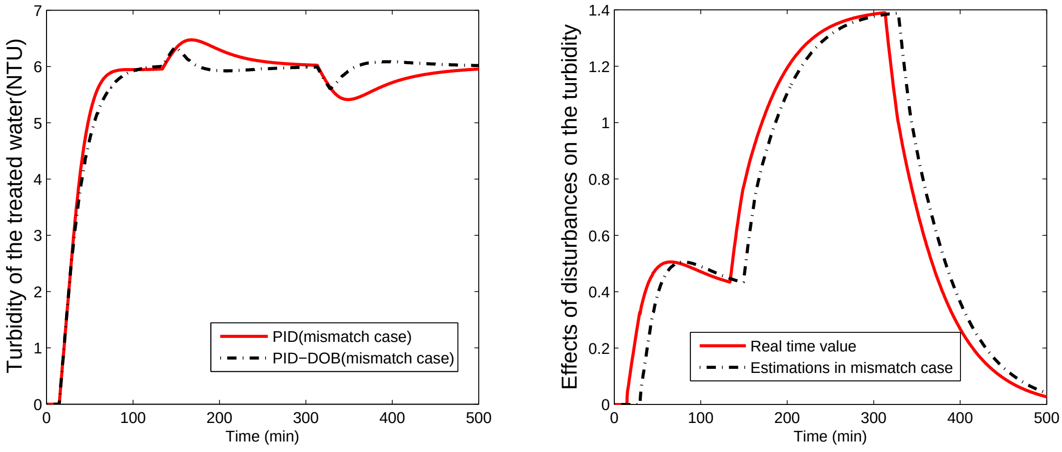
Suppose that the transfer function model of process channel is expressed as

$$G_p(s) = \frac{-1.98}{2430s + 1} e^{-830s}. \tag{15}$$

Comparing (15) with (10), it is clear that severe model mismatch exists.

Model mismatch case: the raw water turbidity has an increase of 15% at $t = 120$min, while the water flow rate has a decrease of 15% at $t = 300$min.

The response curves of the turbidity of the treated water under the control of the two methods are shown in Figure 5(a). The effects of lumped disturbances and the estimations are presented in Figure 5(b). Similar to the nominal case, the proposed method possesses a smaller peak overshoot and a faster convergence speed. This means that the proposed method has achieved a much better disturbance rejection performance than the PID method even in the severe model mismatches.



(a) (b)

Figure 5. Response curves of variables under the two methods in the model mismatch case: (a) controlled variable, (b) disturbances and their estimations

Note that, for those water turbidity control systems employing some advanced control methods such as MPC method, the DOB method is also effective to enhance the disturbance rejection performance. The DOB-based feedforward compensation can be considered as a patch to the existing PID/MPC feedback control [9].

5. **Conclusions.** In the coagulation process, various disturbances bring about undesirable influences on constant turbidity of the treated water control system. Many existing methods including PID have limitations in handling strong disturbances. In order to enhance the disturbance attenuation performance, disturbance observer has been introduced. A composite control method combining a feedforwad compensation based on DOB with a feedback regulation based on PID has been developed in this work. Both external disturbances and internal disturbances caused by model mismatches are considered. The test results have demonstrated that, compared to the conventional PID method, the proposed method has exhibited excellent disturbance attenuation performance, such as a smaller overshoot and a shorter settling time. The future research is to employ and verify the proposed method in the real coagulant dosage system.

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