Control of Stable Processes with Dead Time for Deterministic Disturbance Rejection

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Abstract—**This paper proposes a new modified discrete Smith predictor control scheme for stable processes with dead time. The processes are assumed to be of stable first order with time delay, which are commonly used in process industry. The present scheme consists of two parts: predictive disturbance observer (PDOB) and Smith predictor structure. The PDOB scheme exhibits the property of DOB structure which can push the real plant to the nominal plant. Moreover, the PDOB based on DOB structure has an additional predictive filter which can eliminate the time delay of estimated disturbance, so that the control scheme could compensate deterministic disturbances in dead-time processes. Meanwhile, the Smith predictor structure in the outer loop is utilized to suppress the effects of time delay. In order to demonstrate the results, different simulation examples for periodic disturbance rejection are shown. The results illustrate that the performance of proposed scheme is better than the recent study for periodic disturbance rejection.**

Keywords- dead time; Smith predictor; PDOB; periodic disturbance; robust stability;

I. INTRODUCTION

Conventional controllers, like PID controllers, are wildly used in process industry, but they display poor performance for maintaining the close loop stability when the dead-time is long [1]. Thus, the issue of designing an excellent dead-time compensator (DTC) for improving the effects of time delay on processes is significant. The first dead-time compensator, the Smith predictor [2], was proposed by Smith in 1959. Unquestionably, Smith predictor is an effective control scheme for dead-time systems. The main advantage is that the control scheme could eliminate dead-time from the close-loop characteristic equation, which simplifies the design of controller just like plants without time delay. However, the scheme still has some drawbacks; for example, the set-point response and disturbance rejection response cannot be achieved simultaneously. Therefore, many modifications of original Smith predictor came up to overcome the limitations, such as the extensions of the Smith predictor to integrating or unstable plants, the capabilities of disturbance rejection and the robustness of the closed loop systems. The Smith predictor and its many modifications have been introduced in references [3-11].

The disturbance observer (DOB) which is often used in motion control field was proposed by Ohnishi [12] in 1987. By using the DOB, the disturbances can be estimated and compensated. Normey-Rico et al. [13] proposed a two-degree-of-freedom DOB structure which could be used to reject step and ramp disturbances in integrating processes with dead time. The scheme in [13] was improved by Zhong [14]. Normey-Rico et al. [15] presented a 2DOF discrete DOB control structure, and propose a simple tuning rule to choose sampling time. However, due to the time delay characteristics, the estimated disturbance always lags the real disturbance and the results will exhibit an offset to the target.

Concerning rejecting periodic disturbances in the dead-time processes, Stojic et al. [16] presented a control scheme which combined internal model principle and Smith predictor structure, so that it can reject deterministic disturbances in integrating processes with dead time. Zhou et al. [17] proposed a modified Smith predictor control scheme for periodic disturbances in stable and unstable processes with dead time. Chen et al. [18] proposed a scheme which combined Astrom's modified Smith predictor with the grey predictor shown an excellent performance in step and periodic disturbance rejection for integrating systems with dead time.

In this paper, a modified Smith predictor control scheme is presented for stable processes with dead time. The scheme combines the predictive disturbance observer (PDOB) and Smith predictor structure to reject deterministic disturbances and compensate the effects of dead time. Especially the periodic disturbances can be eliminated when the frequencies of disturbance are known. The paper is organized as follows: first the simple process models and the PDOB structure are described in Section II. In Section III, the proposed control scheme which combines PDOB and Smith predictor structure is proposed. In Section IV, several simulations of the proposed scheme which compared with recent study are shown. Last, the conclusions are listed in the Section V.

II. Process Model and the Predictive Disturbance Observer Structure

A. Process model

A continuous SISO dead-time system is expressed by:

$$P(s) = G(s)e^{-Ls} \tag{1}$$

where $L > 0$ is a dead time, and $G(s)$ is the undelayed part of system. In order to reduce the number of parameters, the process dynamics can be represented by the time delay. In this paper, the first-order plus a dead time (FOPDT) model $P_s(s)$ is considered. i.e.,

$$P_s(s) = \frac{K_p}{\tau s + 1}e^{-Ls} \tag{2}$$

where K_p is static gain, τ is process time constant. Assumed that the delay time is a multiple of the sampling time, so the relation between delay time and sampling time is expressed as: $L = dT$. A discrete version of the process is given as $P(z)$, which is the z-transform of the product of process and zero order holder, that is, $P(z) = \mathrm{Z}\{P(s)(1-e^{Ts})/s\}$ .Then, the discrete process model can be described as:

$$P_n(z) = \frac{\hat{b}}{z-\hat{a}}z^{-d_n} = G_n(z)z^{-d_n} \tag{3}$$

And the process is expressed as:

$$P(z) = \frac{b}{z-a}z^{-d} = G(z)z^{-d} \tag{4}$$

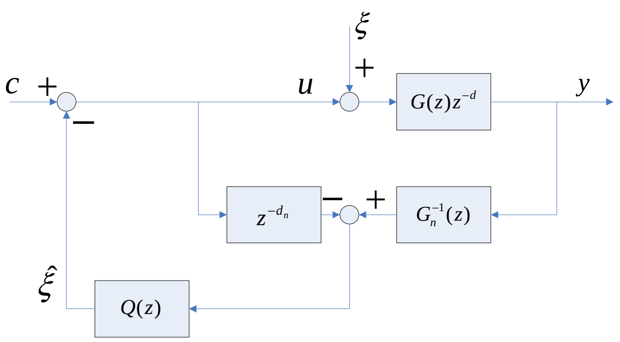

Figure 1. Original DOB structure

where $a = e^{-T/\tau}$ and $b = K_p(1-e^{-T/\tau})$ when the process is FOPDT. In nominal case, the model parameters are the same with real process parameters. This means that: $a = \hat{a}$, $b = \hat{b}$ and $d = d_n$.

B. Original DOB and Predictive disturbance observer structure

The original DOB structure applied to dead-time system is shown in Fig. 1, where $Q(z)$ is a low-pass filter. c , ξ and y are the command, disturbance and output, respectively. $\hat{\xi}$ is estimated disturbance. Thus, the discrete process output could be expressed as follows

$$Y(z) = (U(z) + \xi(z))G_n(z)z^{-d_n} \tag{5}$$

where $U(z)$ is control input. Then, Eq. (5) can be rewritten as:

$$z^{-d_n}\xi(z) = G_n^{-1}(z)Y(z) - z^{-d_n}U(z) \tag{6}$$

Hence, the estimated disturbance could be obtained:

$$\hat{\xi}(z) = Q(z)z^{-d_n}\xi(z) \tag{7}$$

From (7), the estimated disturbance will be affected by the dead time clearly. Therefore, the disturbance could not be eliminated completely when using $Q(z)$ which is just a low-pass filter in original DOB structure.

The deterministic disturbances which could be predicted exactly must satisfy the following property:

$$\phi_\xi(q^{-1})\xi(k) = 0 \tag{8}$$

where $\phi_\xi(q^{-1})$ is a polynomial, and $\xi(k)$ denotes disturbance. The disturbances are characterized by (8), and most common characteristic equations are shown in Table Ⅰ.

TABLE I.

Disturbance	$\phi_\xi(q^{-1})$
Step	$1-q^{-1}$
Ramp	$(1-q^{-1})^2$
Parabolic	$(1-q^{-1})^3$
Sinusoid	$1-2q^{-1}\cos(\omega_0 T)+q^{-2}$

ω_0 : The frequency of sinusoidal disturbance

Note that there is no need to know about the deterministic disturbances precisely. For instance, for a step disturbance, the exact value of the disturbance is not required. Also, the same token applies to the slope of the disturbance for a ramp disturbance. Similarly, the only needs for a sinusoidal disturbance are the frequency and the sampling time. By using (8), the i-step-ahead prediction of deterministic disturbances could be expressed as:

$$\phi_\xi(q^{-1})\xi(k+i) = 0 \tag{9}$$

Since the i-step-ahead prediction of deterministic disturbances is a function composed of data up to $t = k$, the Diophantine equation is used to acquire the prediction of disturbance $\xi(k+i)$. By solving the Diophantine equation, the solutions of (10): E_i and F_i are obtained, and then (10) can be rewritten as (11).

$$\frac{1}{\phi_\xi} = E_i + q^{-i}\frac{F_i}{\phi_\xi} \tag{10}$$

$$E_i\phi_\xi = 1 - q^{-i}F_i \tag{11}$$

where E_i and F_i are polynomials. And (9) is multiplied by E_i :

$$E_i\phi_\xi(q^{-1})\xi(k+i) = 0 \tag{12}$$

Substituting the relation (11) to (12), one may further obtain the following equation.

$$\xi(k+i) = F_i\xi(k) \tag{13}$$

An important result derived from (13) is that the future value of disturbance $\xi(k+i)$ could be obtained by multiplying F_i to $\xi(k)$. Therefore, applying the above property, the time delay exists in the estimated disturbance can be eliminated when adding F_i to traditional DOB structure.

The modified DOB structure is called predictive DOB structure, which can eliminate the input disturbances in dead time systems. In this work, the proposed modification of DOB structure is used as the inner loop. The PDOB control structure based on a DOB structure is shown in Fig. 2, which has an extra predictive filter $F(z)$. The differences between DOB and PDOB structure are that the PDOB structure compensates time delay by the predictive filter and the capacity of disturbance rejection is more superior than only by filter $Q(z)$ in DOB structure.

In the nominal case, $G(z) = G_n(z)$ and $d = d_n$, the closed-loop transfer functions from the command c and the disturbance ξ to the output are derived, respectively:

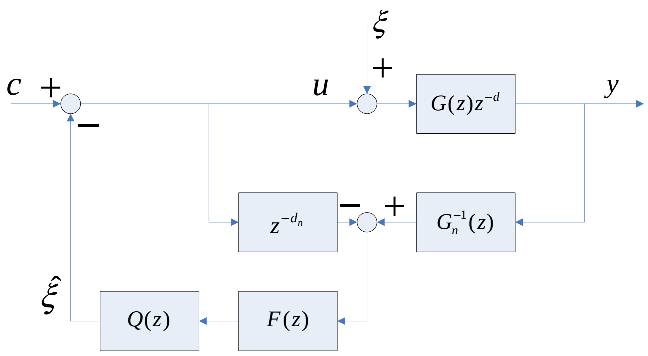

Figure 2. Proposed PDOB structure

$$\frac{y(z)}{c(z)} = G_n(z)z^{-d_n} \tag{14}$$

$$\frac{y(z)}{\xi(z)} = G_n(z)z^{-d_n}\left(1 - Q(z)F(z)z^{-d_n}\right) \tag{15}$$

where $F(z)$ is obtained from $F(q^{-1})$ .To reject the input disturbances, the disturbance response must be zero in the steady state. According to the final value theorem, $Q(z)$ must meet the following condition:

$$\lim_{z\to 1}(z-1)G_n(z)z^{-d_n}\cdot\left[1 - Q(z)F(z)z^{-d_n}\right]\cdot\xi(z) = 0 \tag{16}$$

As shown in (16), to reject different kinds of disturbance, the corresponding predictive filter should be obtained by solving the Diophantine equation first. Therefore, the time delay can be eliminated by utilizing the predictive filter. Finally, the design of Q-filter must satisfy (16), so that the disturbance response is canceled. The detail of the Q-filter design is introduced in the following subsection.

C. Q-filter design

To reject step disturbance, the first order Q-filter is designed as follows:

$$Q(z) = \frac{t_0}{z+\beta} \tag{17}$$

where t_0 and β are the tuning parameters. The filter needs to be unit DC gain and satisfy (16), that is, $\lim_{z\to 1}\frac{t_0}{z+\beta}=1$. Thus, the tuning parameters t_0 and β have the constraint of

$$t_0 = 1+\beta \tag{18}$$

The tuning parameters of the Q-filter may boil down to one parameter. When one parameter β is determined, then the other one parameter t_0 will be obtained immediately.

For ramp disturbance, $\left(1-Q(z)F(z)z^{-d_n}\right)$ must have two roots at $z=1$. This means that:

$$\begin{cases} \lim_{z\to 1}\left(1-Q(z)F(z)z^{-d_n}\right)=0 \\ \lim_{z\to 1}\frac{d}{dz}\left(1-Q(z)F(z)z^{-d_n}\right)=0 \end{cases} \tag{19}$$

Consider the Q-filter is a second order filter as follows:

$$Q(z)=\frac{t_1 z+t_0}{(z+\beta)^2} \tag{20}$$

where t_1, t_0 and β are the tuning parameters. From (19), if the final value of disturbance response is equivalent to zero, the tuning parameters t_1, t_0 and β need to satisfy the constraints of

$$\begin{cases} t_1 = 2\beta+2 \\ t_0=\beta^2-1 \end{cases} \tag{21}$$

For sinusoidal disturbance rejection, the Q-filter is also designed as a second order filter.

$$Q(z)=\frac{t_1 z+t_0}{(z+\beta)^2} \tag{22}$$

To reject sinusoidal disturbances, the following equation must be satisfied:

$$1-Q(z)F(z)z^{-d_n}\Big|_{z=e^{\pm j\omega_0 T}}=0 \tag{23}$$

Therefore, the steady state of sinusoidal disturbance response will become zero, if

$$\lim_{z\to 1}(z-1)\frac{b}{z-a}z^{-d_n}\cdot\left[1-\frac{t_1 z+t_0}{(z+\beta)^2}\right]\cdot\frac{\sin(\omega_0 T)z}{z^2-2\cos(\omega_0 T)z+1}=0$$

Consequently, the parameters t_1, t_0 and β must fulfill the constraints of

$$\begin{cases} t_1 = 2\beta+2\cos(\omega_0 T) \\ t_0=\beta^2-1 \end{cases} \tag{24}$$

III. DESIGN OF MODIFIED SMITH PREDICTOR

Although the PDOB structure in the inner loop is applied to compensate the deterministic disturbances in dead-time systems as presented in Section 2, a controller in the outer loop designed for meeting desired set-point response is required certainly. In this section, a modified Smith predictor structure for stable dead-time processes is proposed.

A. *Proposed control scheme*

In general, the closed loop set-point response and disturbance rejection response must be satisfied, which means that the 2DOF controller is necessary. The proposed control scheme of the modified discrete Smith predictor which could be divided into the modified Smith predictor and the PDOB structure for controlling stable processes is depicted in Fig. 3, where $K(z)$ is a PI-form controller and $R(z)$ is a low-pass filter. These two controllers are tuned to compromise between the disturbance rejection performance and robustness. The outer loop of proposed scheme, that is, modified Smith predictor structure has been proposed in [19] to improve the robustness of conventional Smith predictor. $W(z)$ is a reference filter which is designed to achieve the desired closed loop set-point response. When $Q(z)=0$ and $R(z)=W(z)=1$, the standard Smith predictor structure is obtained.

Assumed that the model perfectly matches the real process, i.e. $G(z)=G_n(z)$ and $d=d_n$, the closed-loop transfer functions from the reference command r and the disturbance ξ to the output are obtained as:

$$H_r(z)=\frac{y(z)}{r(z)}=\frac{K(z)G(z)}{1+K(z)G(z)}W(z)z^{-d} \tag{25}$$

$$\begin{aligned} H_\xi(z)=\frac{y(z)}{\xi(z)}&=\frac{G(z)z^{-d}}{1+K(z)G(z)} \\ &\times\left(1+K(z)G(z)-K(z)G(z)R(z)z^{-d}\right) \\ &\times\left(1-Q(z)F(z)z^{-d}\right) \end{aligned} \tag{26}$$

Then the closed loop response can be obtained as

$$Y(z)=H_r(z)r(z)+H_\xi(z)\xi(z)$$

As shown in (25), the major benefit of the Smith predictor is that the time delay will not appear in the characteristic equation of the closed loop system. Therefore, the design of controller is simplified for the set-point and disturbance response when the model is a perfect representation of the plant. From (26), although the transfer function from disturbance to output has an additional part $(1-QFz^{-d})$ by utilizing the PDOB structure, the structure is stable. Therefore, the control scheme is able to handle the deterministic disturbance.

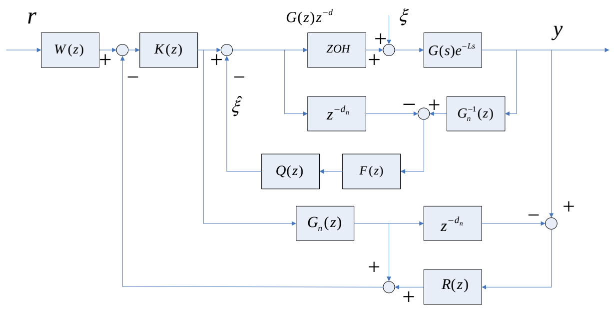

Figure 3. Fig. 3 Discrete modified Smith predictor structure

B. *Design of outer-loop controller*

1) *Tuning of $K(z)$*

The controller is chosen in PI form:

$$K(z)=v_1\frac{z-v_2}{z-1} \tag{27}$$

where v_1 is the proportional action and v_2 is the integral action. This method is similar to the one in [10] where the controller is designed in continuous time.

We may choose $v_1=c_1/b$ and $v_2=a$, so that the controller $K(z)$ becomes

$$K(z)=\frac{c_1}{b}\left(\frac{z-a}{z-1}\right) \tag{28}$$

2) *Design of $R(z)$*

The filter $R(z)$ which is defined as a first order low-pass filter is like in [19], and it can be used to enhance the robustness of conventional Smith predictor structure with decreasing the speed of disturbance rejection.

$$R(z)=\frac{1+\gamma}{z+\gamma},\ -1<\gamma<0 \tag{29}$$

where γ is tuning parameter. The robustness of system increases with γ which goes closely to -1, but the speed of disturbance rejection is slow down. In contrast, the robustness of system decreases with γ which goes closely to 0, but the speed of disturbance rejection increases.

C. *Design of inner-loop Q-filter*

From (26), to reject deterministic disturbances, the steady state of the disturbance response must be zero, that is, the final value is zero.

$$\begin{aligned}Y_\xi(\infty)&=\lim_{z\to1}(z-1)\frac{G(z)z^{-d}}{1+K(z)G(z)}\\&\times\left(1+K(z)G(z)-K(z)G(z)R(z)z^{-d}\right)\\&\times\left(1-Q(z)F(z)z^{-d}\right)\cdot\xi(z)\end{aligned} \tag{30}$$

Once the controllers $K(z)$, $G_n(z)$, $R(z)$ and $F(z)$ are selected as in the previous statements, the Q-filter is utilized to meet the condition of (30).

By substituting $K(z)=c_1(z-a)/\left(b(z-1)\right)$, $G_n(z)=b/(z-a)$ and $R(z)=(1+\gamma)/(z+\gamma)$ into (30), the final value of nominal disturbance response for FOPDT plant can be obtained:

$$\begin{aligned}Y_\xi(\infty)&=\lim_{z\to1}(z-1)\frac{bz^{-d}}{(z-1)(z-a)+c_1(z-a)}\\&\times\left((z-1)+c_1(1-\frac{1+\gamma}{z+\gamma}z^{-d})\right)\left(1-Q(z)F(z)z^{-d}\right)\cdot\xi(z)\end{aligned} \tag{31}$$

From (31), it can be shown that there is no root at $z=1$ for $\frac{bz^{-d}}{(z-1)(z-a)+c_1(z-a)}\left((z-1)+c_1(1-\frac{1+\gamma}{z+\gamma}z^{-d})\right)$. The steady state of the disturbance response will be zero if

$$\lim_{z\to1}(z-1)\left(1-Q(z)F(z)z^{-d}\right)\cdot\xi(z)=0 \tag{32}$$

According to (16) and (32), it is obvious that the design Q-filter is the same as the one of PDOB scheme for disturbance rejection if the process is FOPDT.

The corresponding Q-filter is introduced as follows. Assuming the disturbance is a step input, one designs the Q-filter as a first order filter which is the same as (17):

$$Q(z)=\frac{1+\beta}{z+\beta} \tag{33}$$

For ramp disturbance rejection, the second order Q-filter is the same as (20):

$$Q(z)=\frac{(2\beta+2)z+(\beta^2-1)}{(z+\beta)^2} \tag{34}$$

To reject sinusoidal disturbances, the Q-filter is chosen as (22):

$$Q(z)=\frac{(2\beta+2\cos(\omega_0 T))z+(\beta^2-1)}{(z+\beta)^2} \qquad (35)$$

where β is the only tuning parameter, and it must satisfy the constraint: $-1<\beta<0$.

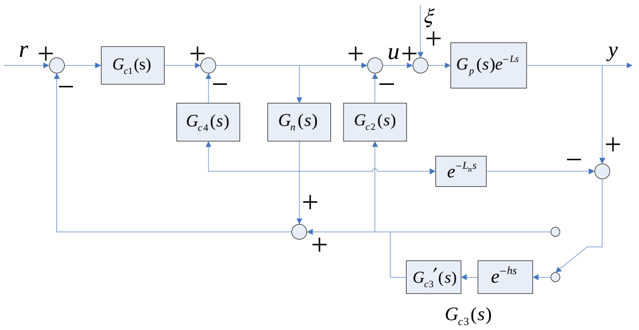

Figure 4. Modified Smith predictor control system proposed by Zhou et al. [17]

D. *Design of* $W(z)$

The filter $W(z)$ is a reference filter, also called pre-filter, which is utilized to achieve the desired set-point response. The formula is described as follows

$$W(z)=\left[\frac{KG}{1+KG}\right]^{-1}\left(\frac{1-w}{z-w}\right) \qquad (36)$$

where w is the tuning parameter. In nominal case, if the filter $W(z)$ is selected as (36), the closed loop transfer function from reference command to output is rewritten as:

$$H_r(z)=\frac{1-w}{z-w}z^{-d} \qquad (37)$$

Consequently, the closed loop set-point transfer function will be a first order system with dead-time in the nominal case.

IV. Simulation Results

In order to illustrate the performance and robustness of proposed control scheme for sinusoidal disturbance rejection, two simulation examples are shown in this section. In this work, the results for stable plants will be compared with Zhou et al. [17], where the control scheme is shown in Fig. 4.

Example 1: Stable processes

Consider a FOPDT process studied in [17]:

$$P(s)=\frac{1}{5.414s+1}e^{-16.05s}$$

Assume a periodic disturbance to be the form

$$\xi(t)=\sin(\omega t)$$

The frequency of the disturbance ω is $2\pi(\text{rad/s})$ when the disturbance is injected from the moment of $t=30$ to the moment of $t=80$. And then the frequency of disturbance changes to $\pi(\text{rad/s})$ after $t=80$. The amplitude of the disturbance is unity. For stable processes, there is no needs to stabilize the inner loop, i.e., $G_{c2}=G_{c4}=0$ in Zhou's method. In [17], the following model was considered: $P_n(s)=P(s)=1/(5.414s+1)e^{-16.05s}$. The controllers were shown as following: $G_{c1}(s)=1+1/5.414s$, $G_{c3}(s)=(5.414s+1)/(\alpha s+1)e^{-hs}$ where $\alpha=5.414/N$, $N=200$ and $h=0.95$. But h changed to 0.95 after $t=80$.

By utilizing the proposed method, the model is obtained as follows: $P_n(s)=P(s)=\dfrac{e^{-16.05s}}{(5.414s+1)}$. If a sampling period $T=0.01(\text{s})$ is chosen, the discrete model is given:

$$G_n(z)=\frac{0.0018}{z-0.9982}$$

The controllers are obtained, respectively:

$$R(z)=\frac{0.005}{z-0.995};\ K(z)=\frac{0.03}{0.0018}\frac{(z-0.9982)}{z-1}$$

$$Q(z)=\frac{(2\beta+2\cos(\omega_0 T))z+(\beta^2-1)}{(z+\beta)^2},\ \beta=-0.95 \quad ;$$

$$W(z)=\frac{0.00185}{z-0.99815}\left(\frac{KG_n}{1+KG_n}\right)^{-1}$$

Before $t=110$, the predictive filter $F(z)$ is designed as $F(z)=(5.86274z-4.9214)/z$. After $t=110$, the corresponding predictive filter $F(z)$ is $F(z)=(5.9655z-4.9803)/z$. With above controller settings, this proposed method is compared with Zhou et al. [17] in the nominal case. In Fig. 5a, it is obvious that the periodic disturbance is completely eliminated by the proposed scheme. Fig. 5b shows that the effect of periodic disturbance can be attenuated markedly, but the disturbance still leads steady state error in system output by the control scheme in [17]. It means that the proposed method gives a better performance in the sinusoidal disturbance rejection by comparing Fig. 5a with Fig. 5b. In [17], the periodic disturbance is compensated by adding an extra time delay, so that it will take more time in disturbance rejection when the process delay is not a multiple of the period of disturbance. Therefore, it will be more effective in the transient response by this proposed method.

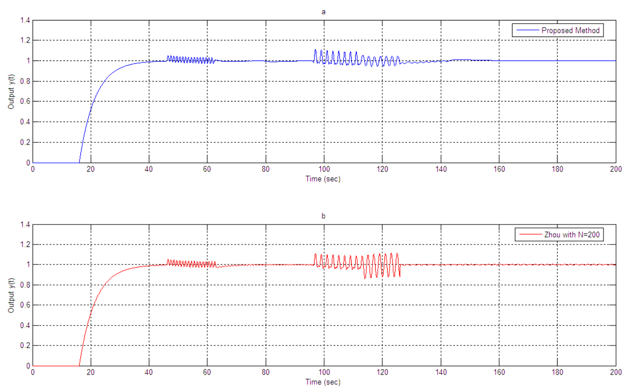

Figure 5. 5a and 5b System response for a stable plant.

Example 2: Stable processes with delay uncertainty

Consider a FOPDT process studied in [17]:

$$P(s)=\frac{1}{5.414s+1}e^{-16.05s}$$

where a disturbance is the same as the one in Example 1, except for the frequency of disturbance. The frequency of disturbance is $\pi/8(\text{rad/s})$ in the example. By utilizing Zhou's method, the controller parameters are designed as example 1, but only one h is changed to 15.95. In proposed control scheme, the model is considered as $G_n(z)=b/(z-a)$, where $b=0.0018$ and $a=0.9982$. The controllers $K(z)$, $F(z)$, $R(z)$ are designed as following:

$$R(z)=\frac{0.005}{z-0.995};\ K(z)=\frac{0.001}{0.0018}(\frac{z-0.9982}{z-1})$$

$$F(z)=(5.9994z-4.9997)/z$$

$$Q(z)=\frac{(2\beta+2\cos(\omega_0 T))z+(\beta^2-1)}{(z+\beta)^2},\ \beta=-0.994\qquad;$$

$$W(z)=\frac{0.00185}{z-0.99815}(\frac{KG_n}{1+KG_n})^{-1}$$

Consider that the process is the same with process model, the system response shown in Fig. 5a and 5b are obtained. Fig. 6a shows the system response in the proposed method, and Fig. 6b presents the result by mean of the scheme in Zhou. From Figs. 6a and 6b, they illustrate that the disturbance response of the proposed method is faster than the one of Zhou's method. The result can be attributed to that the MSE obtained by utilizing proposed scheme is 0.0704, and the MSE given by using Zhou's method is 0.075. If the actual dead time varies to $L=15.2$, the results under the same controllers are shown in Fig. 7. From Fig. 7, the plant becomes unstable by using Zhou's method, but the plant is still stable by our proposed method.

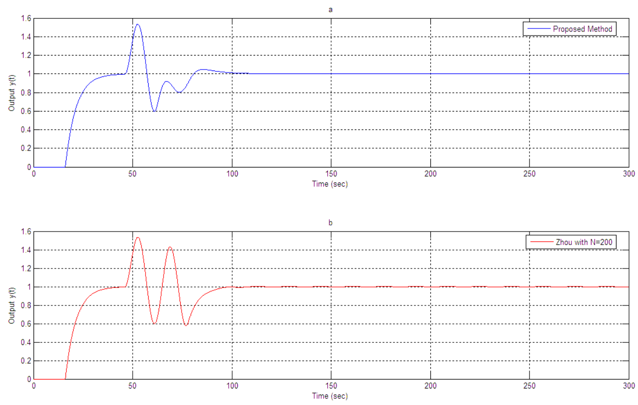

Figure 6. 6a and 6b System response if the model is perfect match process.

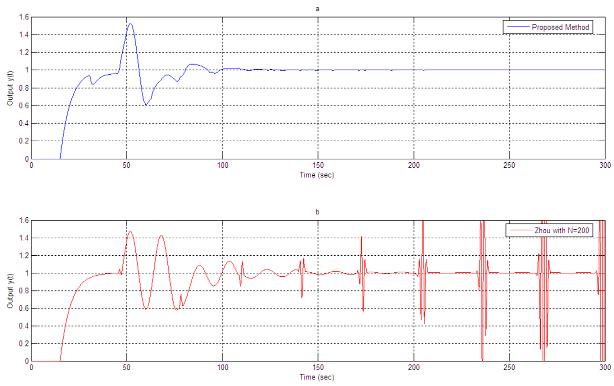

Figure 7. System response for a dead time 15(s) , a unit sinusoidal disturbance at t = 40(s)

V. Conclusions

In this paper, a new modified Smith predictor structure for deterministic disturbance rejection has been proposed, and the common simple models such as stable first order processes with time delay and an integrator with time delay are considered. This control scheme comprises Smith predictor structure in outer loop and PDOB structure in inner loop. The former, Smith predictor is used to compensate the effect of dead time, and the latter, PDOB structure can be utilized to reject deterministic disturbances, especially for periodic disturbances. Finally, for periodic disturbance rejection, several simulations which are compared with [17] demonstrate that better performance and robustness are achieved by using the proposed control scheme.

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