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Robust Smith Predictor (RSP)

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Abstract—**As is well known, control of industrial processes with significant dead time by using the conventional Smith Predictor (SP) results better performance in comparison to PI controllers. The SP has a main disadvantage which is a lack of robustness to variations in process parameters. To eliminate this deficiency, this paper presents the Robust Smith Predictor which is based on a modified disturbance observer to estimate disturbance and a filter instead of the Smith controller. The conducted simulations show that the proposed Robust Smith Predictor can eliminate the Smith predictor deficiency in robustness and provide an elegant trade-off between disturbance rejection and robustness.**

Keywords- Dead time; Smith predictor; Robustness; Disturbance rejection; Trade-off

I. Introduction

Desire control of processes with significant dead time may be difficult using PI controllers. The Smith Predictor (SP) structure was developed at the end of the 1950s as a first dead time compensator structure to enhance the performance of PI or PID controllers for dead time process [1-4]. The SP has its own advantages and disadvantages. Its main advantage is that the dead time is effectively taken outside the control loop in the transfer function relating the process output to reference. On the other hand, lack of robustness to variations in process parameters is the SP dominant disadvantage [5].

Different modifications have been introduced in order to enhance the robustness of the SP structure [5-11]. Maybe the Double Controller Scheme (DCS) proposed by Tian and Gao is the most efficient one [12]. Unfortunately, disturbance rejection deteriorates regard to the SP structure [5].

This paper presents the Robust Smith Predictor (RSP) to improve the above mentioned drawback of the SP. The RSP is based on a modified disturbance observer to estimate an input disturbance and a filter instead of the Smith controller. The proper trade-off between robustness and disturbance rejection can be obtained by means of only one tuning parameter. On the other hand, the reference tracking is adjusted by one tuning parameter. The implemented simulations shows capability of the RSP in providing an elegant trade-off between disturbance rejection and robustness and remarkable improvement for reference tracking.

The rest of this paper is organized as follows. The concept of the Internal Model Control (IMC) is reviewed in Section II. The SP and the DCS structure is expressed in Section III. The introduced RSP is proposed in section IV. Section V contains simulation studies. Conclusion is presented in Section VI.

II. Internal Model Control

IMC is a control strategy which introduced by Rivera et al. Its main advantage is that it allows us to consider model uncertainty and trade-offs between performance and robustness in a more systematic way [13].

In Fig. 1, $G_p(s)e^{-sTp}$ and $G_m(s)e^{-sTm}$ are the process and process model respectively. G_{IMC} represents the IMC controller. Assume that the process model is perfectly same to the process, i.e., $G_m(s)e^{-sTm} = G_p(s)e^{-sTp}$. Then the output y to the reference and the disturbance can be expressed as

$$y = G_p G_{IMC} e^{-sT_p} r + \left(1 - G_p G_{IMC}\right) G_p e^{-sT_p} d \quad (1)$$

Suppose that $G_p = G_m$, $T_p = T_m$ and G_p is of minimum phase-shift. Then the controller is simply choose as follows

$$G_{IMC}(s) = G_p^{-1}(s) f(s) \quad (2)$$

where, $f(s)$ is a user-specified function with $f(0) = 1$. A common choice of $f(s)$ is as follows

$$f(s) = \frac{1}{\left(T_f s + 1\right)^r} \quad (3)$$

Here, T_f is a positive real constant and r is a positive integer. By tuning T_f, one can control the trade-off between the performance and robustness monotonously [14]. The resultant closed-loop response to the reference and the disturbance is

$$y = fe^{-sT_p} r + G_p e^{-sT_p} \left(1 - fe^{-sT_p}\right) d \quad (4)$$

Note that perfect tracking except pure time-delay is achieved by choosing $f \equiv 1$. Fig. 2 shows a two degree of freedom (2DOF) IMC structure. In the 2DOF IMC structure, G_{c1}(s) stands for the robust stability and the disturbance rejection and G_{c2}(s) defines the tracking [15].

III. Smith Predictor and Double Controller Scheme

Fig. 3 presents the SP structure which consists of a primary controller G_c, delay free plant G_p, delay free plant model G_m, plant dead time e^{-sTp} and estimated dead time e^{-sTm}.

In Fig. 3, y is output, r is the reference and d is the input disturbance. The closed-loop transfer functions for such a structure can be expressed as:

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$$\frac{Y(s)}{R(s)}=\frac{G_c(s)G_p(s)e^{-sT_p}}{1+G_c(s)G_m(s)+G_c(s)\left[G_p(s)e^{-sT_p}-G_m(s)e^{-sT_m}\right]} \quad (5)$$

$$\frac{Y(s)}{D(s)}=\frac{\left(1+G_c(s)G_m(s)\left(1-e^{-sT_m}\right)\right)e^{-sT_p}}{1+G_c(s)G_m(s)+G_c(s)\left[G_p(s)e^{-sT_p}-G_m(s)e^{-sT_m}\right]} \quad (6)$$

Supposing the perfect model condition, $G_m(s)e^{-sTm} = G_p(s)e^{-sTp}$, removes the delay component from the closed loop characteristic equation and consequently, delay issues can be ignored when designing the controller.

The SP has a major deficiency in comparison to the PI controller which is lack of robustness to variations in process parameters [2]. To solve this problem, Tian and Gao introduced the DCS, as shown in Fig. 4. The resultant closed-loop transfer functions are as follows:

$$\frac{Y(s)}{R(s)}=\frac{G_{c1}(s)G_p(s)e^{-sT_p}\left(1+G_{c2}(s)G_m(s)e^{-sT_m}\right)}{\left(1+G_{c1}(s)G_m(s)\right)\left(1+G_{c2}(s)G_p(s)e^{-sT_p}\right)} \quad (7)$$

$$\frac{Y(s)}{D(s)}=\frac{G_p(s)e^{-sT_p}}{1+G_{c2}(s)G_p(s)e^{-sT_p}} \quad (8)$$

As can be seen from Eqs. (7) and (8), in the case of perfect match the reference tracking and disturbance rejection are decoupled from each other and consequently, are controlled independently by $G_{c1}(s)$ and $G_{c2}(s)$, respectively.

In the DCS structure, as can be seen in Fig. 4, any mismatch between the plant $G_p(s)e^{-sTp}$ and its model $G_m(s)e^{-sTm}$ can be considered as an additional disturbance [12]. Since the resultant closed-loop transfer function to the disturbance is the same as for a control scheme with a PI controller, it can be concluded that the robustness improves [5]. Although disturbance rejection is much more important than reference tracking for many process control applications, the DCS disturbance rejection deteriorates regard to the SP [5].

IV. ROBUST SMITH PREDICTOR

To eliminate the SP deficiency in robustness, this paper proposed RSP. After separating SP structure as shown in Fig. 5, one can obtain the observer oriented form of the SP structure as shown in Fig. 6. Consequently, the SP structure can be considered as a special case of the 2DOF IMC in which it has only one controller to control robust stability, the disturbance rejection and the tracking simultaneously. From Fig. 6, one can consider the tracking controller ($G_{tracking}$) as

$$G_{tracking}=\frac{G_c(s)}{1+G_c(s)G_m(s)}=G_p^{-1}(s)F_1(s) \quad (9)$$

$F_1(s)$ is a user-specified filter with $F_1(0) = 1$. A simple choice of $F_1(s)$ is given in Eq. (3). T_{f1} controls the tracking speed as an adjustable parameter. Generally, increasing T_{f1} decreases the response speed and makes it more robust and vice versa. On the other hand, from Fig. 6, the following equation can be obtained

$$Y_{obs}=\frac{G_m(s)G_c(s)e^{-sT_m}}{1+G_m(s)G_c(s)}D(s) \quad (11)$$

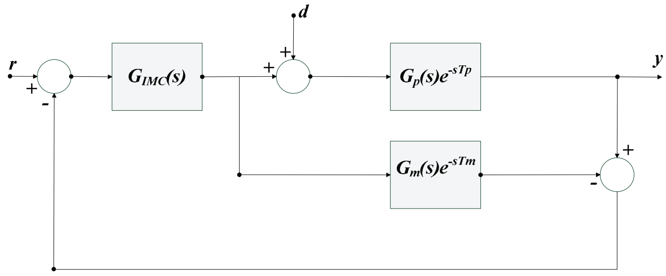

Figure 1. IMC Structure

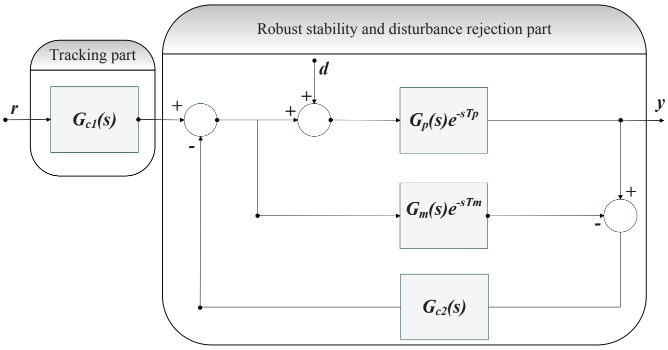

Figure 2. Two degree of freedom IMC Structure

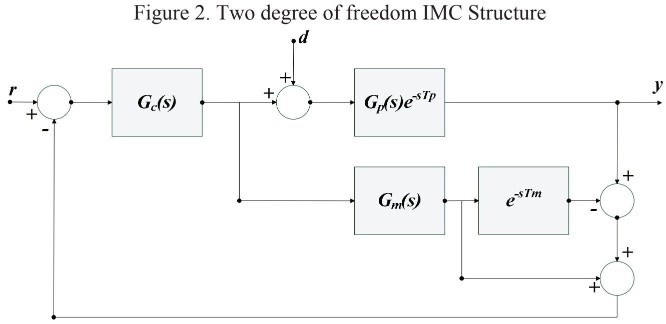

Figure 3. Smith predictor Structure

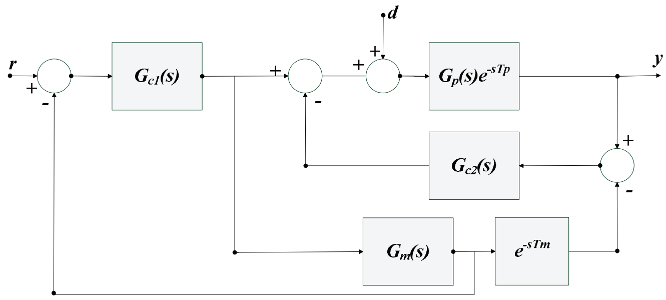

Figure 4. Double controller scheme structure

If disturbance is considered to be a step function, the following relation can be reached

$$\lim_{t\to\infty} y_{obs}(t)=\frac{G_m(0)G_c(0)}{1+G_m(0)G_c(0)}d \quad (12)$$

Where d is the steady state value of input disturbance. Consequently, if

$$k=\frac{1+G_m(0)G_c(0)}{G_m(0)G_c(0)}, \quad G_m(0)G_c(0)\neq 0 \quad (13)$$

Then the value of kY_{obs} will be as follows

$$\lim_{t\to\infty} ky_{obs}(t)=d \quad (14)$$

Which, shows that second part of the SP structure works as disturbance observer. As a result, the disturbance response is separated from the tracking response. Subsequently, this paper introduced a filter instead of Smith controller to control tradeoff between the performance and robustness as shown in Fig. 7. Where $F_2(s)$ is a user-specified filter with $F_2(0) = 1$. A simple choice of $F_2(s)$ is given in Eq. (3). By tuning T_{f2}, one can control the tradeoff between the disturbance rejection and robustness monotonously.

V. SIMULATION RESULTS

The RSP was compared with the SP and the DCS. The parameters of the RSP, the SP and the DCS controllers for plants G_{p1} and G_{p2} are shown in Table I and II in which, K_m, T_m, a_m are the calculated plant model parameters which identified manually.

$$G_1 = \frac{e^{-6s}}{s+1} \tag{16}$$

$$G_2 = \frac{e^{-10s}}{(s+1)(0.5s+1)(0.25s+1)(0.125s+1)} \tag{17}$$

As a tuning parameters, T_{f1} is set 0, 0.5, 1 and 2 to show its capability in controlling the tracking speed and T_{f2} is set 1, 5, 10 and 30 to show its trade-off capability.

The closed loop response obtained for a step change in the reference signal and the disturbance on nominal plant G_{p1} and G_{p2} are shown in Fig. 8 to 11 respectively. As can be seen from Figs. 8 and 10, fastest reference tracking reached by RSP at $T_{f1} = 0$ in which T_{f2} is set 10. In other words, reference tracking with the RSP improves with decreasing T_{f1}. Figs. 9 and 11 shows that disturbance rejection with the RSP improves with decreasing T_{f2}. In other words, disturbance rejection of the RSP with T_{f2}=1 is fastest one and with T_{f2}=30 is slowest one.

In order to test robustness to variations in plant parameters, the simulation were repeated for a 20% increase in gain, 50% increase in all time constants and 15% increase in dead time. The closed loop response with variations in the process parameters are shown in Figs. 12 to 24. Fig. 12 and 15 shows that in the case of 20% increase at the plant gain, fastest reference tracking reached by RSP at T_{f2} =1 and fastest disturbance rejection reached by RSP at T_{f2}=1.

Fig. 16 and 19 shows that in the case of 50% increase at the plant time constants, the faster reference tracking reached by RSP at T_{f2}=1 and fastest disturbance rejection reached by RSP at T_{f2}=1. As a result, performance of the RSP particularly improves by decreasing T_{f2}.

When the dead time is increased by 15% it can be obviously seen in Fig. 20 and 23 that robustness of the RSP particularly improves by increasing T_{f2}. It can be clearly seen that the RSP robustness with T_{f2} =10 and 30 is better than the SP and the DCS. It seems that, a good reference tracking and a good trade-off between disturbance rejection and robustness can be reached by RSP around T_{f1}=1 and T_{f2}=10.

TABLE I. PARAMETERS OF THE DCS, SP AND RSP FOR PROCESS $G_{P1}(S)$

Controller	K_m	T_m	a_m	K_{p1}	T_{i1}	T_{d1}	K_{p2}	T_{i2}
DCS	1	6	1	1	1	-	0.33	3
SP	1	6	1	1	1	-	-	-
RSP	1	6	1	1	-	1	-	-

TABLE II. PARAMETERS OF THE DCS, SP AND RSP FOR PROCESS $G_{P2}(S)$

Controller	K_m	T_m	a_m	K_{p1}	T_{i1}	T_{d1}	K_{p2}	T_{i2}
DCS	1	10.5	1.5	1	1.5	-	0.3	4.5
SP	1	10.5	1.5	1	1.5	-	-	-
RSP	1	10.5	1.5	1	-	1.5	-	-

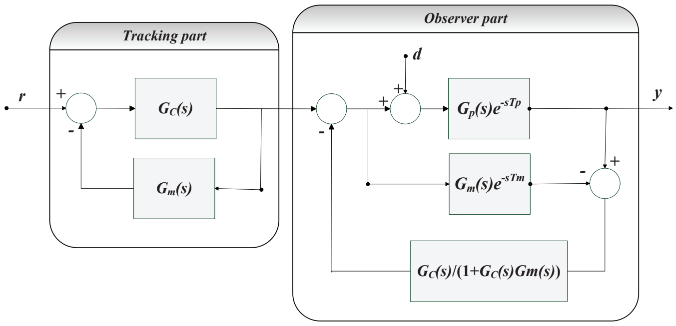

Figure 5. Smith predictor Structure: separated form

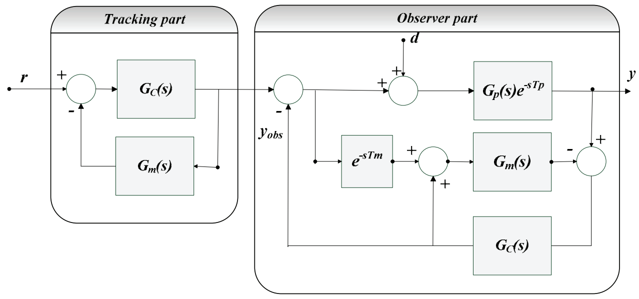

Figure 6. Smith predictor Structure: observer form

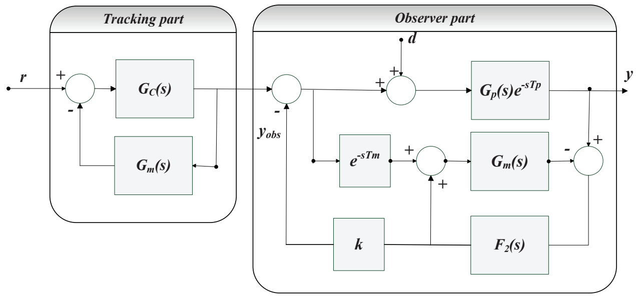

Figure 7. Robust Smith Predictor Structure

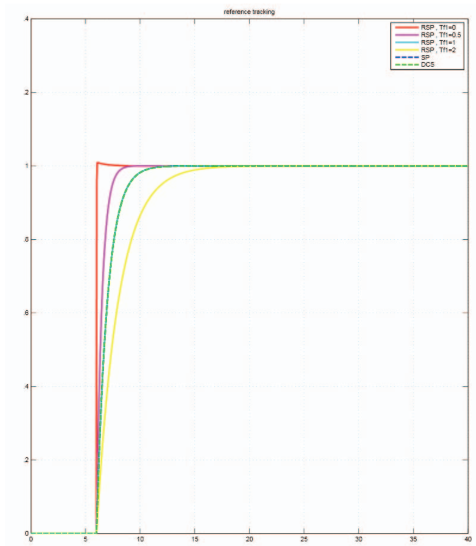

Figure 8. Reference tracking of the nominal process G_{p1} for T_{f2} = 10

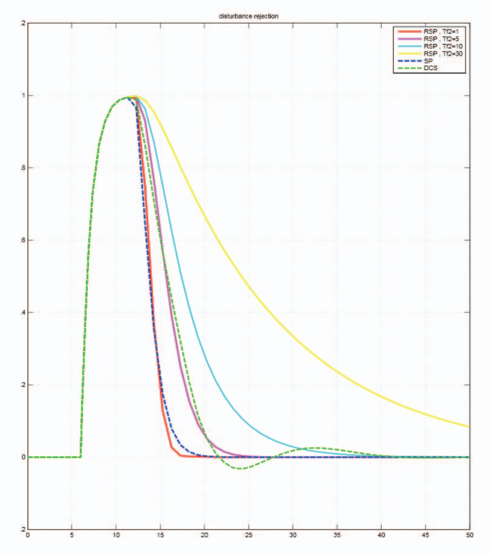

Figure 9. Disturbance rejection of the nominal process G_{p1}

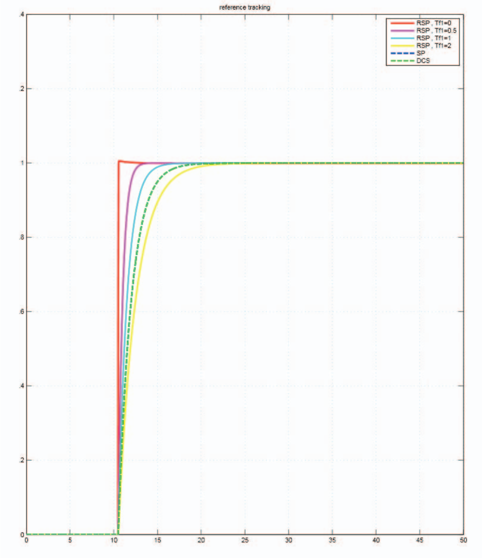

Figure 10. Reference tracking of the nominal process G_{p2} for $T_{f2} = 10$

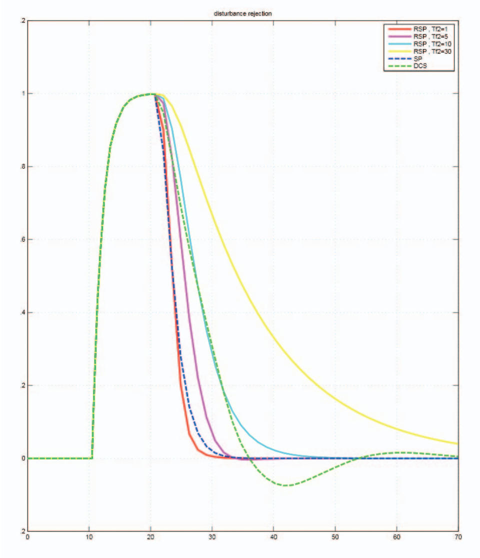

Figure 11. Disturbance rejection of the nominal process G_{p2}

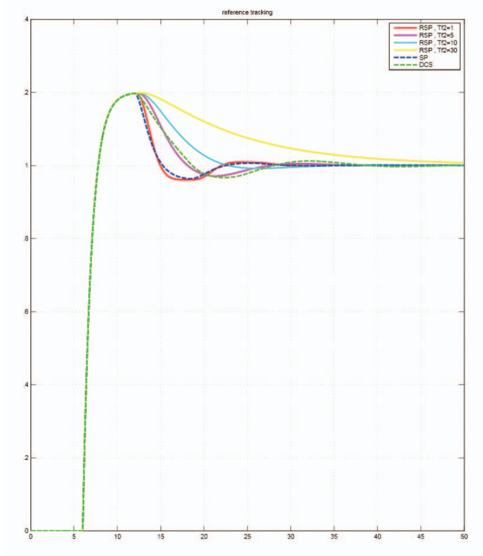

Figure 12. Reference tracking of G_{p1} with gain increased by 20%

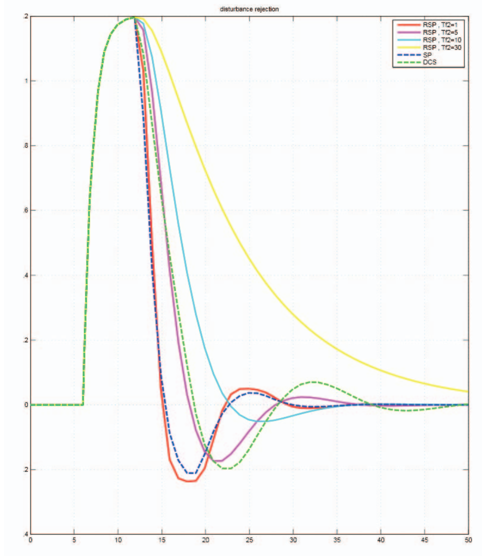

Figure 13. Disturbance rejection of G_{p1} with gain increased by 20%

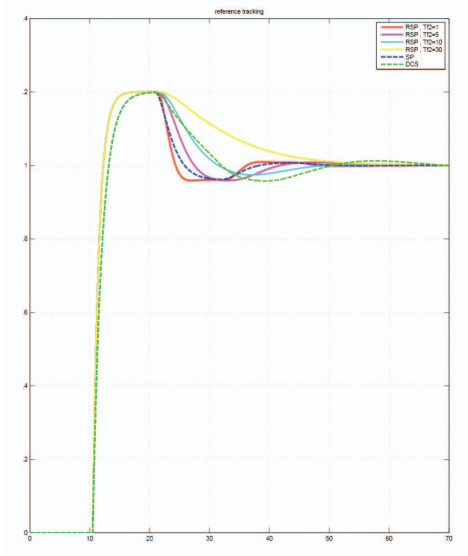

Figure 14. Reference tracking of G_{p2} for T_{f1}=1 with gain increased by 20%

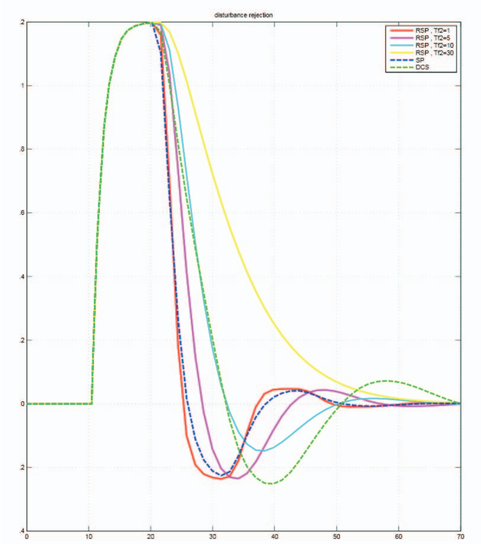

Figure 15. Disturbance rejection of G_{p2} with gain increased by 20%

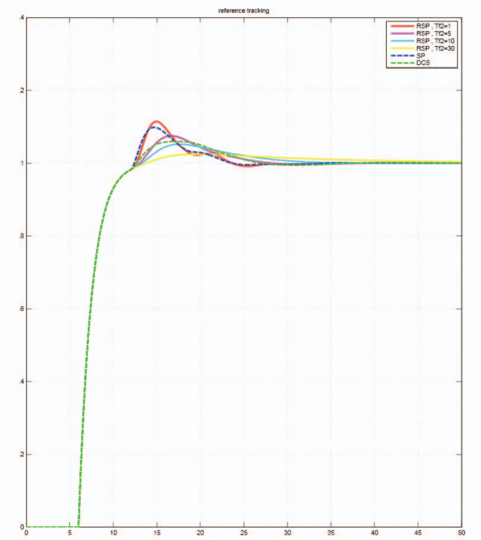

Figure 16. Reference tracking of G_{p1} with time constant increased by 50%

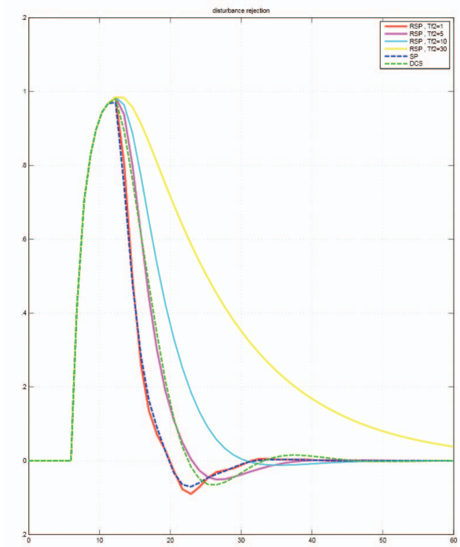

Figure 17. Disturbance rejection of G_{p1} with time constant increased by 50%

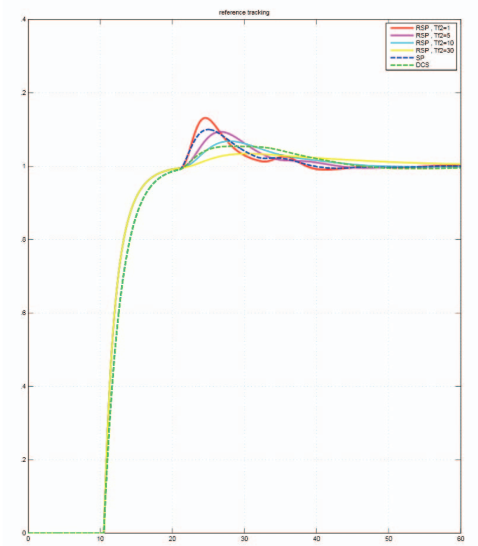

Figure 18. Reference tracking of G_{p2} with time constant increased by 50%

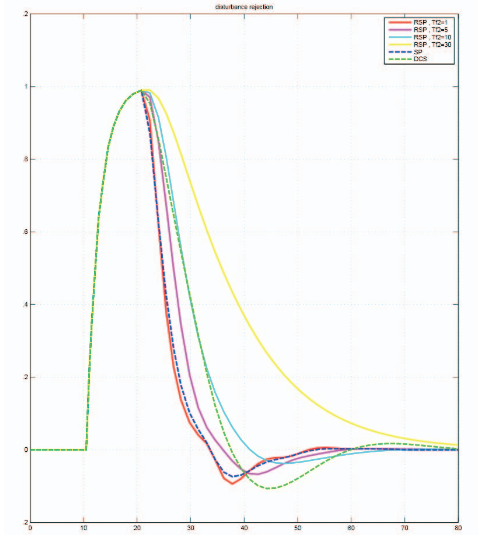

Figure 19. Disturbance rejection of G_{p2} with time constant increased by 50%

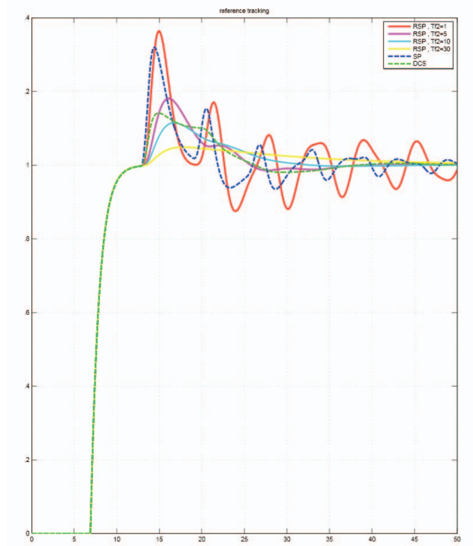

Figure 20. Reference tracking of G_{p1} with dead time increased by 15%

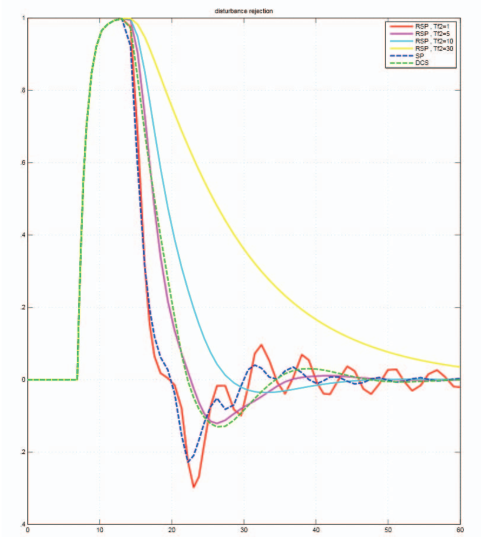

Figure 21. Disturbance rejection of G_{p1} with dead time increased by 15%

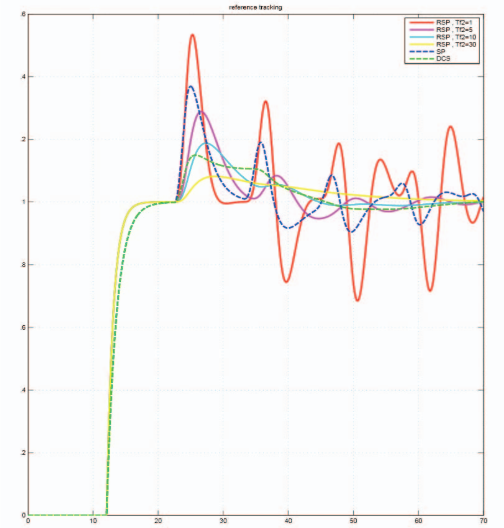

Figure 22. Reference tracking of G_{p2} with dead time increased by 15%

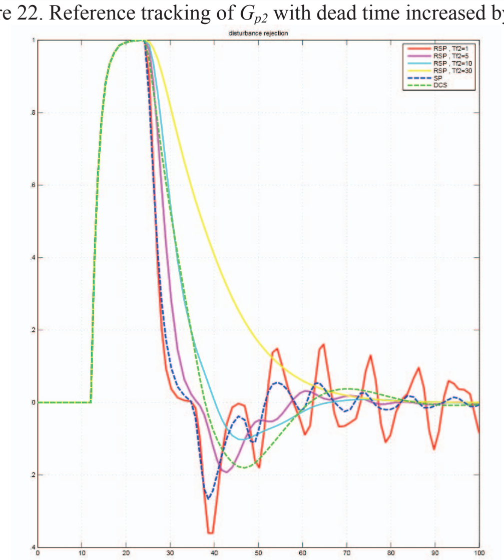

Figure 23. Disturbance rejection of G_{p2} with dead time increased by 15%

VI. Conclusion

This paper proposed Robust Smith Predictor (RSP) based on a modified disturbance observer and a filter to eliminate the Smith predictor deficiency in robustness to variations in process parameters especially in time delay. The main features of the proposed RSP are fourfold. First, it maintains SPs advantages like its simple structure. Second, the disturbance response is separated from the tracking response. Third, the tracking response and disturbance response can be tuned by only two adjustable parameters respectively. Fourth, it provides an elegant trade-off between disturbance rejection and robustness. The robustness of the proposed RSP is clear from results reached by conducted simulations, and its advantages regard to the SP and the DCS are evident, as well.

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