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A NEW SMITH PREDICTOR FOR CONTROLLING A PROCESS WITH AN INTEGRATOR AND LONG DEAD-TIME: DESIGN AND TUNING

Ljubiša S. Draganović, Milić R. Stojić and Milan S. Matijević

Abstract: This paper proposes a new Smith predictor for controlling a process with an integrator and long dead times. The structure comprises the classical Smith controller, in the main control loop, and the disturbance estimator, in the local minor loop. The main feature of the structure consists in ability to reject the constant, ramp, and slow varying unmeasurable external disturbances. The controlling structure in this paper allows more freedom in choosing controller parameters in order to improve both the set-point response and efficiency of disturbance rejection.

Key words: Smith predictor, process controlling, PID controller, PI controller, disturbance estimator.

1. Introduction

Smith predictor (SP) has been proposed in the late fifteens as one among first structures of predictive control suggested for controlling a process having a long dead time [1], [2]. The structure enables the closed-loop system characteristic equation to be derived in the polynomial form, without the transcendental term $\exp(-Ls)$ describing a time delay. It has been shown [3] that the classical SP cannot be used for controlling a process with an integrator. Namely, in the presence of integration mode $1/s$ within the process transfer function, a constant disturbance produces a nonzero steady-state

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Lj.S. Draganović is with the LOLA Institute, 11000 Belgrade.

M.R. Stojić is with the University of Belgrade, Electrical Engineering Faculty, 11120 Belgrade (e-mail ESTOJIC@ubbg.etf.bg.ac.yu).

M.S. Matijević is with the University of Kragujevac, Faculty of Mechanical Engineering, 34000 Kragujevac.

error. To overcome this obstacle, the modified structure of SP has been proposed in [3] by including the I-action into the main controller of PI or PID type. For the same purposes, other modifications of SP has been recently proposed [3]-[8] for compensation of the process transport lag. All of these compensations require the setting of more parameters of the process and main controller. See, for example, [9] where the tuning of PID controller within the modified SP is presented.

Majority of papers concerning SP modifications considers the possibility of reduction of number of adjustable parameters [3]-[6], [8]. The robust PI controller with three tuning parameters has been proposed in [6]. Åström *et al.* [7] suggested a new SP with disturbance estimator (DE) in which the set-point response and disturbance response are decoupled and thus may be adjusted independently. However, the control algorithm proposed in [7] requires setting of six parameters in the case when the estimated value of process velocity gain is mismatched. In [8], the structure of SP with PI controller and joined fixed filter is presented and the structure tuning is performed by placing poles of a simplified second order closed-loop system characteristic equation. The comparative study of different schemes of modified SP was given in [10] and [11].

In this paper we consider a new SP extended by DE. Unlike other modifications of SP designed to reject a constant disturbance, the control scheme proposed in this paper enables the rejection of the constant, ramp, and a wide class of slow varying disturbances. The tuning of proposed control structure is based upon the application of M circle method [12] and pole placement procedure.

2. Control System Structure

Figure 1 shows the proposed control structure, which comprises the process, SP as a main controller, and DE, in the local minor loop, which is used to obtain disturbance estimate $\hat{d}(t)$. From Fig. 1, one can easily derive the relations between the inputs and outputs of DE. The relations may be presented by vector equation

$$\begin{bmatrix} y(s) \\ \hat{d}(s) \end{bmatrix} = \frac{1}{1+\dfrac{A(s)}{C(s)}G_p(s)} \begin{bmatrix} [1+\dfrac{A(s)}{C(s)}G_m(s)]G_p(s) & G_p(s) \\ \dfrac{A(s)}{C(s)}[G_p(s)-G_m(s)] & \dfrac{A(s)}{C(s)}G_p(s) \end{bmatrix} \begin{bmatrix} u(s) \\ d(s) \end{bmatrix} \tag{1}$$

where the following notation is used: $y(s)$ system output, $d(s)$ external disturbance, $\hat{d}(s)$ disturbance estimate, $u(s)$ control variable, $G_p(s)$ transfer function of integrative process with dead time, $G_m(s)$ nominal transfer function of integrative process with dead time, $G_{m1}(s)$ nominal transfer function of integrative process without dead time, $A(s)/C(s)$ transfer function of disturbance controller.

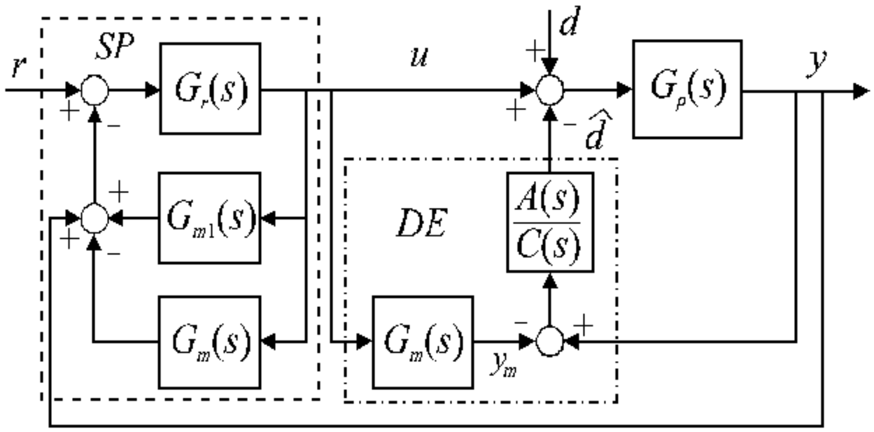

Fig. 1. Controlling structure of modified Smith predictor.

In a particular (nominal) case when $G_p(s) \equiv G_m(s)$, one can derive from (1)

$$\begin{aligned} y(s) &= \left[\left(1+\frac{A(s)}{C(s)}G_m(s)\right)G_p(s)u(s)+G_p(s)d(s)\right]\frac{1}{1+\frac{A(s)}{C(s)}G_p(s)} \\ &= G_p(s)u(s)+\frac{G_p(s)}{1+\frac{A(s)}{C(s)}G_p(s)}d(s) \end{aligned} \tag{2}$$

and

$$\hat{d}(s) = \frac{\frac{A(s)}{C(s)}G_p(s)}{1+\frac{A(s)}{C(s)}G_p(s)}d(s). \tag{3}$$

Hence, in the nominal case, the estimation error $d(s) - \hat{d}(s)$ becomes

$$d(s) - \hat{d}(s) = \frac{1}{1 + \dfrac{A(s)}{B(s)} G_p(s)} d(s). \tag{4}$$

In virtue of the structure of Fig. 1 and equations (2) and (3), the following closed-loop system transfer functions are derived

$$\frac{y(s)}{r(s)} = \frac{G_r(s) G_p(s) \left[1 + \dfrac{A(s)}{C(s)} G_m(s)\right]}{\left[1 + \dfrac{A(s)}{C(s)} G_p(s)\right] \left[1 + G_{m1}(s) G_r(s)\right] + G_r(s) \left[G_p - G_m(s)\right]} \tag{5}$$

and

$$\frac{y(s)}{d(s)} = \frac{G_p(s) \left[1 + G_{m1}(s) G_r(s) - G_m(s) G_r(s)\right]}{\left[1 + \dfrac{A(s)}{C(s)} G_p(s)\right] \left[1 + G_{m1}(s) G_r(s)\right] + G_r(s) \left[G_p - G_m(s)\right]}. \tag{6}$$

In the nominal case ($G_p(s) \equiv G_m(s)$), equations (5) and (6) are reduced to

$$\frac{y(s)}{r(s)} = \frac{G_r(s) G_m(s)}{1 + G_{m1}(s) G_r(s)} \tag{7}$$

and

$$\frac{y(s)}{d(s)} = \frac{G_m(s)[1 + G_{m1}(s) G_r(s) - G_m(s) G_r(s)]}{\left[1 + \dfrac{A(s)}{C(s)} G_m(s)\right] \left[1 + G_{m1}(s) G_r(s)\right]}. \tag{8}$$

For the analysis in this paper, integrative industrial processes will be considered and described by the following transfer function

$$G_p(s) = \frac{K_\nu}{s(T_1 s + 1)(T_2 s + 1) \cdots (T_n s + 1)} e^{-\tau s}, \tag{9}$$

where K_ν is the process velocity gain factor, τ is the process dead time, and T_i ($T_i > 0, i = 1, 2, \ldots, n$) are process time constants. The process transfer function may be rewritten as

$$G_p(s) = \left[\frac{K_\nu}{s} + \Delta G(s)\right] e^{-\tau s}, \tag{10}$$

with

$$\Delta G(s) = \frac{k_1}{T_1 s + 1} + \frac{k_2}{T_2 s + 1} + \cdots + \frac{k_n}{T_n s + 1}, \tag{11}$$

where residues k_i $(i = 1, 2, \ldots, n)$ are functions of velocity gain K_ν and process time constants T_i. For a long process dead time, one can assume the nominal process model as

$$G_m(s) = \frac{K_\nu}{s} e^{-Ls}, \tag{12}$$

where L is an identified effective transport lag and $\Delta G(s)$ in (11) is unmodeled process dynamics. The nominal process model without transport lag is

$$G_{m1}(s) = \frac{K_\nu}{s}. \tag{13}$$

For an integrative process (9), the proper choice is the proportional main controller

$$G_r(s) = K_r. \tag{14}$$

With (12) - (14), closed-loop system transfer functions (7) and (8) become

$$\frac{y(s)}{r(s)} = \frac{K_r \dfrac{K_\nu}{s} e^{-Ls}}{1 + K_r \dfrac{K_\nu}{s}} \tag{15}$$

and

$$\frac{y(s)}{d(s)} = \frac{\dfrac{K_\nu}{s} e^{-Ls} \left[1 + \dfrac{K_\nu}{s} K_r - \dfrac{K_\nu}{s} K_r e^{-Ls}\right]}{\left[1 + \dfrac{K_\nu}{s} K_r\right] \left[1 + \dfrac{A(s)}{C(s)} \dfrac{K_\nu}{s} e^{-Ls}\right]}. \tag{16}$$

The closed-loop system transfer function (15) has the single real pole $s = -K_r K_\nu$. Thus, after setting an estimated value of K_ν, the desired speed of set-point transient response can be matched by choosing an appropriate value of proportional gain, K_r i.e., setting the desired time constant $T_d = 1/K_r K_\nu$. From (16) it is seen that the disturbance response is governed by roots of closed-loop system characteristic equation

$$\left[1 + \frac{K_\nu}{s} K_r\right] \left[1 + \frac{A(s)}{C(s)} \frac{K_\nu}{s} e^{-Ls}\right] = 0. \tag{17}$$

Hence, after choosing the value of time constant T_d, the speed of disturbance rejection may be adjusted independently by synthesizing the DE transfer function $A(s)/C(s)$.

3. Parameter Setting

First, we consider the case when both the reference and disturbance are constant, $r(t) = 1(t)$, $d(t) = 1(t)$. Then the steady-state error is calculated from (15) and (16) by

$$y(\infty) = \left.\frac{K_\nu K_r e^{-Ls}}{s + K_\nu K_r}\right|_{s=0} + \left.\frac{K_\nu e^{-Ls}[s + K_\nu K_r - K_\nu K_r e^{-Ls}]C(s)}{[s + K_\nu K_r]\,[C(s) + A(s)K_\nu e^{-Ls}]}\right|_{s=0}. \quad (18)$$

If a chosen polynomial $C(s)$ is stable and $A(0) \neq 0$, from (18) one obtains and the steady-state error is equal to zero. Hence, the inherent feature of the controlling structure of Fig. 1 is the ability to reject constant disturbances.

3.1 Setting by M circles

The closed loop characteristic equation of DE is given by (17). After choosing an appropriate value of time constant $T_d = 1/K_r K_\nu$, the speed of disturbance rejection is resolved by placing roots of equation

$$1 + \frac{A(s)}{C(s)}\frac{K_\nu}{s}e^{-Ls} = 0. \quad (19)$$

Case 1

In the simplest case, we choose $A(s) = K_A$ and $C(s) = 1$. Then equation (19) becomes $1 + W(s) = 0$ with

$$W(s) = \frac{K_A K_\nu}{s}e^{-Ls}. \quad (20)$$

For an aperiodical disturbance response, frequency characteristic $W(j\omega)$ must touch M circle of infinite radius (indexed by $M = 1$) [12] as it is shown in Fig. 2. In that case,

$$R = \mathrm{Re}\{W(j\omega)\} \approx -\frac{K_A K_\nu}{\omega}\sin(L\omega) = -\frac{1}{2}. \quad (21)$$

For relatively small values of $L\omega$ in radians, and $\sin(L\omega) \approx L\omega$ from (21) one obtains

$$K_A = \frac{0.5}{K_\nu L}. \quad (22)$$

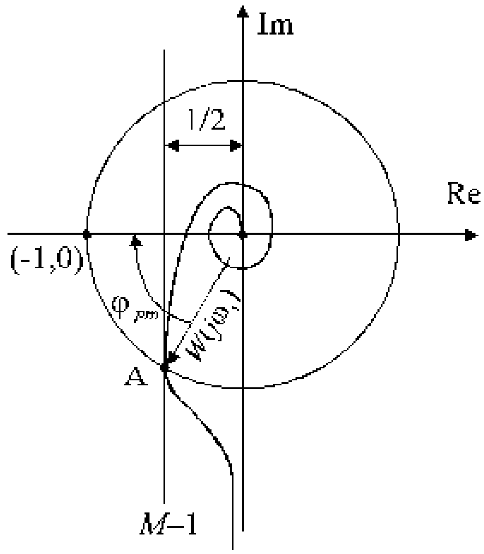

Fig. 2. M circles in $W(j\omega)$-plane.

Case 2

In the second case, we choose $A(s) = K_A(T_A s + 1)$ and $C(s) = 1$. Now, for an aperiodical disturbance response, the entire hodograph of

$$W(j\omega) = \frac{K_A K_\nu}{j\omega}(T_A j\omega_1)e^{-Lj\omega} \tag{23}$$

must lie on the right-hand side of the straight line $R = -1/2$ in the (R, I)-plane, where $R = \mathrm{Re}\{W(j\omega)\}$ and $I = \mathrm{Im}\{W(j\omega)\}$. The parameters K_A and T_A of DE are calculated from intersection (point A in Fig. 2) of the M circle and unit circle $R^2 + I^2 = 1$. Recall that this corresponds to the phase margin $\phi_{pm} = \pi/3$ radians or

$$\begin{aligned}\phi_{pm} =& \pi + \arg W(j\omega_1)\\ =& \frac{\pi}{2} + \arctan(T_A\omega_1) - L\omega_1 = \frac{\pi}{3},\end{aligned} \tag{24}$$

where gain crossing frequency is calculated from

$$|W(j\omega_1)| = \frac{K_A K_\nu \sqrt{T_A^2\omega_1^2 + 1}}{\omega_1} = 1. \tag{25}$$

After substituting $\arctan(T_A\omega_1) \approx T_A\omega_1$, from (24) one obtains

$$\omega_1 = \frac{\pi}{6}\frac{1}{L-T_A}, \qquad L > T_A. \tag{26}$$

On the other hand, from (25) we have

$$\omega_1 = \frac{K_A K_\nu}{\sqrt{1-K_A^2 K_\nu^2 T_A^2}}, \qquad 0 \le K_A K_\nu T_A < 1. \tag{27}$$

Eliminating ω_1 from (26) and (27), it is obtained

$$K_A = \frac{\pi}{6LK_\nu}\frac{1}{\sqrt{1-\frac{2T_A}{L}+\frac{T_A^2}{L^2}+\frac{\pi^2 T_A^2}{36L^2}}}. \tag{28}$$

After utilizing the first order Padé approximation $\exp(-Ls) \approx (1 - Ls/2)/(1 + Ls/2)$ in (19), we assume

$$T_A = \frac{L}{2} \tag{29}$$

in order to cancel $(1 + Ls/2)$ with $(T_A s + 1)$ in equation (19) with $A(s) = K_A(T_A s + 1)$. In doing so and substituting (29) into (28), one obtains

$$K_A \approx \frac{0.927}{K_\nu L}. \tag{30}$$

3.2 Setting by pole placement

Case 3

Let us assume lead compensator $A(s)/C(s)$ with

$$A(s) = K_A(T_A s + 1) \qquad \text{and} \qquad C(s) = T_C s + 1, \qquad (T_A > T_C). \tag{31}$$

Then, after using the Padé approximation, characteristic equation (19) becomes

$$1 + K_A\frac{T_A s + 1}{T_C s + 1}\frac{K_\nu}{s}\frac{2-Ls}{2+Ls} = 0, \tag{32}$$

or, in polynomial form,

$$T_C L s^3 + (L + 2T_C - K_A K_\nu T_A L)s^2 + (2K_A K_\nu T_A - K_A K_\nu L)s + 2K_A K_\nu = 0. \tag{33}$$

Parameters K_A, T_A and T_C of DE may be determined according to the desired speed of disturbance response by choosing all roots $-\sigma_1$, $-\sigma_2$, and $-\sigma_3$ of equation (33) to be real negative and equal to each other, $\sigma_1 = \sigma_2 = \sigma_3 = \sigma$, $(\sigma > 0)$ [13]. Then the following relations hold

$$\sigma^3 = \frac{2K_A K_\nu}{T_C L}, \tag{34}$$

$$3\sigma^2 = \frac{2K_A K_\nu T_A - K_A K_\nu L + 2}{T_C L}, \tag{35}$$

$$3\sigma = \frac{2T_C + L - K_A K_\nu T_A L}{T_C L}. \tag{36}$$

Eliminating K_A and T_A from equations (34)-(36), one obtains

$$\left(\sigma + \frac{2}{L}\right)^3 = \frac{8}{T_C L^2} + \frac{16}{L^3}$$

or

$$\sigma = \frac{2}{L}\sqrt[3]{2 + \frac{L}{T_C}} - \frac{2}{L}. \tag{37}$$

Parameter T_C is calculated according to the desired dominant time constant T_{DE} of DE or with respect to the desired speed of rejection of a constant disturbance. Thus, if we assume $\sigma = 1/T_{DE}$, parameter T_C is calculated from (37) as

$$T_C = \frac{8}{L^2}\left[\left(\frac{1}{T_{DE}} + \frac{2}{L}\right)^3 - \frac{16}{L^3}\right]^{-1}, \tag{38}$$

where is

$$\frac{1}{T_{DE}} > \frac{2}{L}\left(\sqrt[3]{2} - 1\right) = \frac{0.5198}{L}.$$

Other two parameters of DE are calculated by substituting $\sigma = 1/T_{DE}$ and T_C from (38) into equations (34) and (35) and solving these equations for to obtain

$$K_A = \frac{T_C L}{2T_{DE}^3 K_\nu}, \tag{39}$$

$$T_A = \frac{4T_{DE}^3}{L^2} + \frac{2T_{DE}^3}{LT_C} - \frac{6T_{DE}^2}{L}. \tag{40}$$

Case 4

In the cases 1-3, two different tuning procedures of DE are given when both the set-point and disturbance are constant. To enable the absorption of ramp and slow varying disturbances the absorption principle [10], [14] is employed. According to the principle, we assume

$$\begin{aligned} A(s) &= K_A(T_A s + 1) \qquad \text{and} \\ C(s) &= T_A s. \end{aligned} \tag{41}$$

Notice that now DE includes the classical PI controller $A(s)/C(s) = K_A(T_A s + 1)/T_A s$, having the proportional gain $K_p = K_A$ and integrative time constant $T_i = T_A$, which ensure the zero steady-state error for a ramp disturbance $d(t) = d_0 t \cdot 1(t)$. After setting (41) and the Padé approximation into (19), characteristic equation (19) can be reduced into polynomial form

$$T_A L s^3 + (2T_A - K_A K_\nu T_A L)s^2 + (2K_A K_\nu T_A - K_A K_\nu L)s + 2K_A K_\nu = 0. \tag{42}$$

Parameters K_A and T_A will be determined using the same procedure of pole placement as in Case 3. Thus we have

$$\sigma^3 = \frac{2K_\nu K_A}{T_A L}, \tag{43}$$

$$3\sigma^2 = \frac{2T_A - K_A K_\nu T_A L}{T_A L} \qquad \text{and} \tag{44}$$

$$3\sigma = \frac{2T_A - K_A K_\nu T_A L}{T_A L}. \tag{45}$$

Eliminating from (43)-(45), one obtains

$$\sigma = \frac{2}{L}\left(\sqrt[3]{2} - 1\right) = \frac{0.51984}{L}, \tag{46}$$

and then, solving equations (43) and (44) for K_A and T_A, we get

$$K_A = \frac{0.44}{K_\nu L} \qquad \text{and} \tag{47}$$

$$T_A = 6.27L. \tag{48}$$

Recall that this DE rejects ramp disturbances; of course, it will reject constant disturbances, too.

Case 5

From (46) it is seen that the triple root σ of characteristic equations depends only of the effective transport lag L. To enable the movement of the root along the negative part of real axis in s plane and thus to fit the desired speed of disturbance rejection, the transform may be employed as

$$e^{-Ls} = e^{-s(\alpha L+\beta L)}, \quad \alpha+\beta=1, \quad 0 \le \alpha < 1 \quad \text{and} \quad 0 < \beta \le 1, \tag{49}$$

to obtain the first order Padé approximation in the form

$$e^{-Ls} = \frac{1-\alpha Ls}{1+\beta Ls}. \tag{50}$$

With (41) and (50) the polynomial form of equation (19) becomes

$$\beta T_A L s^3 + (T_A - \alpha K_A K_\nu T_A L)s^2 + (K_A K_\nu T_A - \alpha K_A K_\nu L)s + K_A K_\nu = 0. \tag{51}$$

Using the same procedure of pole placement as in the cases 3 and 4, one get

$$\sigma^3 = \frac{K_\nu K_A}{\beta T_A L}, \tag{52}$$

$$3\sigma^2 = \frac{K_A K_\nu T_A - \alpha K_A K_\nu L}{\beta T_A L} \quad \text{and} \tag{53}$$

$$3\sigma = \frac{T_A - \alpha K_A K_\nu T_A L}{\beta T_A L}. \tag{54}$$

Solving equations (52)-(54) for σ, K_A and T_A one obtains

$$\sigma = \frac{1}{\alpha L}\left(\sqrt[3]{1+\frac{\alpha}{\beta}} - 1\right), \tag{55}$$

$$K_A = \frac{1-3\beta\sigma L}{\alpha K_\nu L}, \quad \alpha \ne 0 \tag{56}$$

$$T_A = \frac{3}{\sigma} + \alpha L. \tag{57}$$

Notice from equations (55)-(57) that for $\alpha = \beta = 1/2$ these equations become the same as related ones (46)-(48).

Case 6

To demonstrate the ability of the controlling structure of Fig. 1 to reject more complex disturbances, suppose the constant set-point $r(t) = 1(t)$ and sinusoidal disturbance $d(t) = d_0 \sin(\omega_0 t) \cdot 1(t)$. Now, according to absorption principle [13], we assume

$$\begin{aligned} A(s) =& K_A s(T_A s + 1) \qquad \text{and} \\ C(s) =& \frac{s^2 + \omega_0^2}{\omega_0^2}. \end{aligned} \tag{58}$$

With (50) and (58), characteristic equation (19) of DE becomes

$$s^2 + \omega_0^2 + K_A(T_A s + 1) K_\nu \frac{1 - \alpha L s}{1 + \beta L s} = 0, \tag{59}$$

or, after simple rearrangement,

$$\begin{aligned} \beta L s^3 + (1 - \omega_0 K_A K_\nu T_A \alpha L) s^2 + & (\omega_0^2 \beta L - \omega_0 K_A K_\nu \alpha L + \omega_0 K_A K_\nu T_A) s \\ & + \omega_0^2 + \omega_0 K_A K_\nu = 0. \end{aligned} \tag{60}$$

Application of the pole placement, proposed in this paper, yields

$$\sigma^3 = \frac{\omega_0^2 + \omega_0 K_\nu K_A}{\beta L}, \tag{61}$$

$$3\sigma^2 = \frac{\omega_0^2 \beta L - \omega_0 K_A K_\nu \alpha L + \omega_0 K_A K_\nu T_A}{\beta L} \quad \text{and} \tag{62}$$

$$3\sigma = \frac{1 - \omega_0 K_A K_\nu T_A \alpha L}{\beta L}. \tag{63}$$

The solution of (61)-(63) for σ, K_A, and T_A is obtained as

$$\sigma = \frac{1}{\alpha L} \left(\sqrt[3]{1 + \frac{\alpha}{\beta}(1 + \omega_0^2 \alpha L^2)} - 1 \right), \tag{64}$$

$$K_A = \frac{\beta \sigma^3 L - \omega_0^2}{\omega_0 K_\nu}, \qquad \omega_0^2 < \beta \sigma^3 L \tag{65}$$

$$T_A = \frac{1 - 3\beta\sigma L}{\alpha L(\beta \sigma^3 L - \omega_0^2)}, \quad 3\beta\sigma L < 1, \quad \alpha > 0, \quad \omega_0^2 < \beta\sigma^3 L \tag{66}$$

According to (64), by choosing the prper value of α ($\alpha + \beta = 1$) or of dominant time constant $T_{DE} = 1/\sigma$ of the disturbance response, one can adjust the speed sinusoidal disturbance rejection.

4. Examlpes

We consider the process given by [11]

$$G_p(s) = \frac{e^{-5s}}{s(0.9s+1)(0.5s+1)(0.3s+1)(0.1s+1)}, \tag{67}$$

with identified nominal plant model

$$G_m(s) = \frac{1}{s}e^{-6.8s}. \tag{69}$$

In all simulation runs the reference $r(t) = 1(t)$ and dominant time constant of set-point response $T_d = 1/K_r K_\nu = 2$ seconds are adopted.

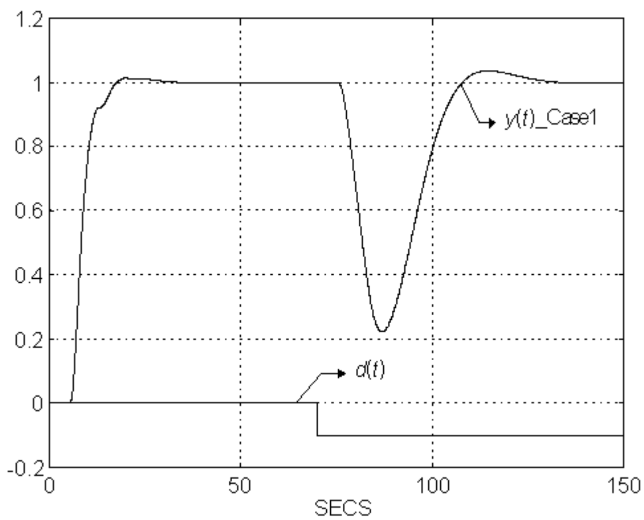

Fig. 3. Absorption of a constant disturbance by the disturbance estimator designed as a P controller.

First, the controling structure of Fig. 1 is designed to absorb the constant disturbance $d(t) = -0.1 \cdot 1(t-70)$. Fig. 3 shows the disturbance response, in the simplest case, when $A(s) = K_A = 0.5/K_\nu L = 0.074$ and $C(s) = 1$ (Case 1). Fig. 4 illustrates the absorption of the same disturbance $d(t) = -0.1 \cdot 1(t-70)$ when DE is designed by the PD controller $A(s)/C(s) = K_A(T_A s + 1)$ with $K_A = 0.136$ and $T_A = 0.5L = 3.4$ (Case 2). By comparing the traces of Figs. 3 and 4, one can conclude that the

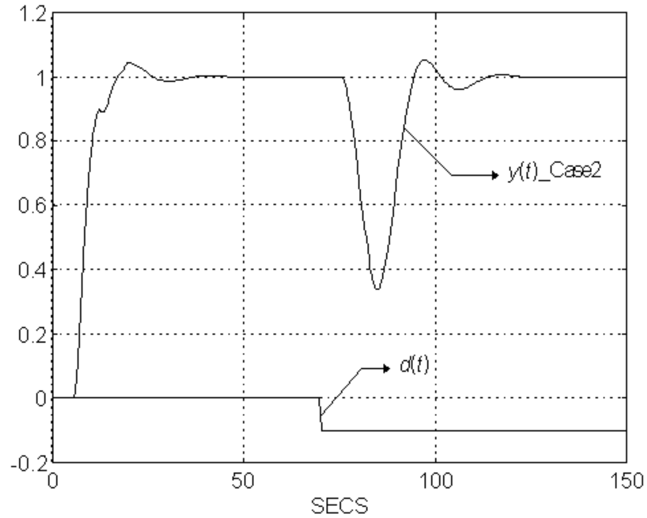

Fig. 4. Absorption of a constant disturbance by the disturbance estimator designed as a PD controller.

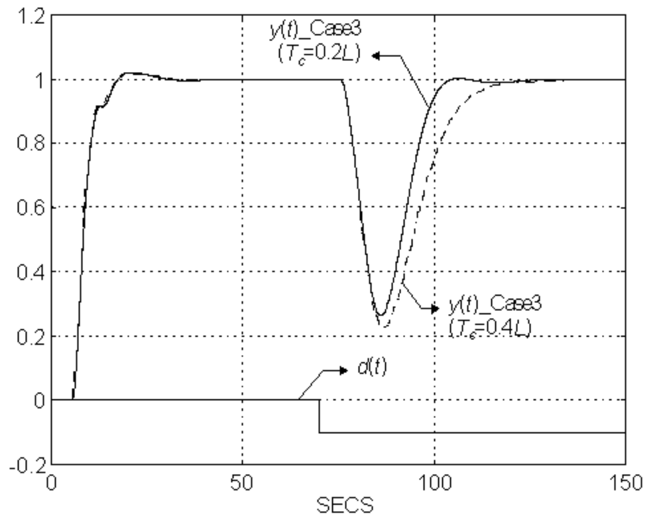

Fig. 5. Absorption of a constant disturbance by the disturbance estimator designed as a lead compensator.

inclusion of D-action in the control law slightly improves the disturbance absorption. A significant improvement of disturbance absorbtion is achieved

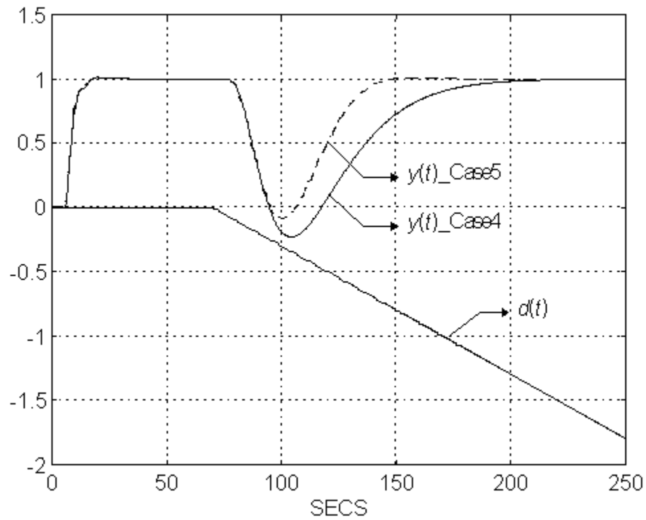

Fig. 6. Absorption of a ramp disturbance by the disturbance estimator designed as a PI controller.

by using the lead compensator $A(s)/C(s) = K_A(T_As+1)/(T_Cs+1)$ (Case 3). The first trace (solid line) of Fig. 5 shows the disturbance response obtained for $K_A = 0.608/K_\nu L = 0.089$, $T_A = 0.5L = 3.4$, $T_C = 0.2L = 1.36$, and $T_{DE} = 0.55L = 3.74$. The second trace (dotted line) of Fig. 5 is obtained for $K_A = 0.44/K_\nu L = 0.065$, $T_A = 0.545L = 3.706$, $T_C = 0.4L = 2.72$, and $T_{DE} = 0.77L = 5.236$.

The first trace (solid line) of Fig. 6 illustrates the ability of controlling structure to absorb ramp disturbance (Case 4). In simulation runs, the same ramp disturbance $d(t) = d_0(t-70)\cdot 1(t-70)$ is applied and the DE is designed by the conventional PI controller $A(s)/C(s) = K_A(T_As+1)/T_As$ with $K_A = 0.44/K_\nu L = 0.065$ and $T_A = 6.27L = 42.636$. To make clear efficiency of Padé approximation (50), the second trace (doted) in Fig. 6 is given. The trace is obtained with the PI controller $A(s)/C(s) = K_A(T_As+1)/T_As$ within DE with $K_A = 0.521/K_\nu L = 0.077$, $T_A = 4.96L = 33.728$, $\alpha = 0.7$ and $\beta = 0.3$.

To demonstrate the ability of controlling structure in absorption of a more complex disturbance (Case 6), the sinusoidal disturbance $d(t) = d_0 \sin[\omega_0(t-37)] \cdot 1(t-37)$ with $\omega_0 = 0.05$ rad/s is applied and DE is designed by $A(s) = K_As(T_As+1)$ and $C(s) = (s^2+\omega_0^2)/\omega_0^2$ with $K_A = 0.332/K_\nu L = 0.049$, $T_A = 4.585L = 31.178$, $\alpha = 0.95$ and $\beta = 0.05$.

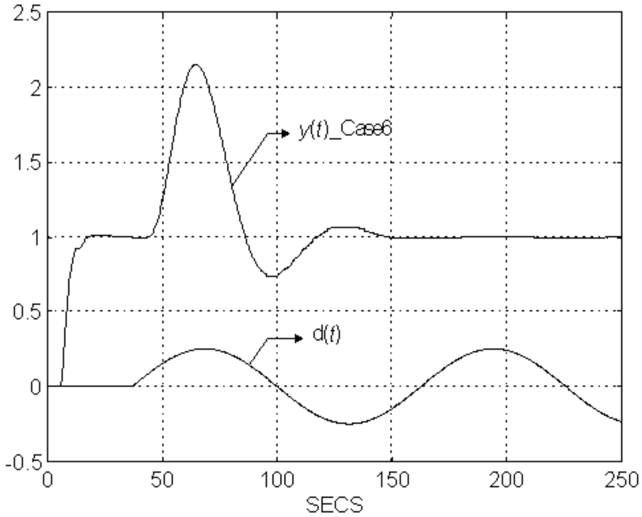

Fig. 7. Absorption of a sinusoidal disturbance by the disturbance estimator designed by using the absorbtion principle.

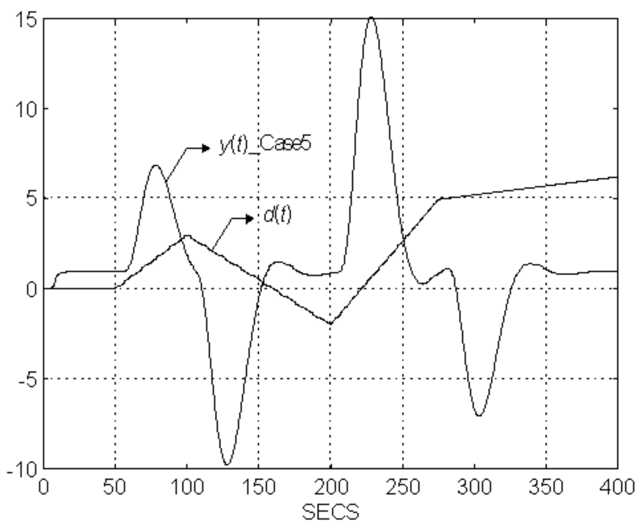

Fig. 8. Absorption of a combined ramp disturbance by the disturbance estimator designed as a PI controller.

Fig. 7 shows that disturbance is absorbed during only one period of oscillations.

Finaly, the more complex ramp disturbance $d(t)$ combined by several linear segments, shown in Fig. 8, is applied in the controlling structure designed to absorb ramp disturbances by $A(s)/C(s) = K_A(T_A s + 1)/T_A s$ and $K_A = 0.627/K_\nu L = 0.092$, $T_A = 3.742L = 25.4456$, $\alpha = 0.85$ and $\beta = 0.15$ (Case 5). From Fig. 8 it is seen that each linear segment of disturbance is absorbed within a relatively small time period.

5. Concluding Remarks

We have proposed a modified structure of the Smith predictor for control plants with the integrating mode, velocity constant, process time constant, and long transport lag. The stucture comprises the classical Smith controller and disturbance estimator. The method based upon the use of M circle and pole placement procedure are applied for parameter setting according to the desired set-point response and speed of disturbance rejection. All tuning parameters, the single parameter of main controller and parameters of disturbance estimator, have clear physical meanings. The observer estimator is designed in different ways to absorb the constant, ramp, slow varyng and sinusoidal disturbances. Several experimental results are present to illustrate the design procedure and to demonstrate the efficiency of the controlling structure in disurbance rejection.

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