Controller Tuning for Integrating Processes with Time Delay Part III: The Case of First Order plus Integral plus Dead-Time Processes

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***Abstract*— In this paper, Pseudo-Derivative Feedback (PDF) controllers are designed for first order plus integral plus dead-time (FOLIPDT) processes. Simple methods for tuning the PDF feedback controller are presented. The PDF control structure and the proposed tuning methods ensure smooth closed-loop response to set-point changes, fast regulatory control and satisfactory robustness against parametric uncertainty. The proposed methods require small computation effort and they are particularly useful for on-line applications. Simulation results show that our methods are favorably compared to the already known PI/ PID controller tuning methods for FOLIPDT processes.**

***Index Terms*— Pseudo-derivative feedback, controller tuning, process control, integrating processes, dead-time processes, first-order lag.**

I. Introduction

INTEGRATING processes are frequently encountered in the process industries. Many chemical and agricultural processes can be modeled, for the purpose of designing controllers, by an integrator plus dead-time (IPDT) model [1]-[6]. This model is able to represent the dynamics of many systems over the frequency range of interest for simple three-term controllers. However, in some cases, IPDT model is inadequate to model process dynamics. For example in the case where the process has both large and small time constants, a simple IPDT model cannot capture system behavior. In this case, alternative types of integrating models with time delay must be used to adequately represent process dynamics. Among them, the first order lag plus integral plus dead time (FOLIPDT) has received great attention in the past [5]-[8].

Controller tuning for FOLIPDT processes has received moderate attention in the past. Few tuning rules for PI/PID controllers have been reported in the literature, for this type of processes. Known PI/PID controller-tuning methods for FOLIPDT processes are based in ultimate cycle information [9], on minimization of IAE [10] and ITAE [11] criteria, on direct synthesis approaches [5] and on robust control techniques [12]-[14]. Alternative modified controller structures, (such as two degree of freedom controllers, series controllers with derivative filtering, non-interacting controllers, controllers with special set-point weighting, etc.) have also been proposed and tuned (see [6] and the references therein). Most of these tuning rules yield large overshoot and settling time, as well as poor robustness.

The goal of the third part of the present paper on controller tuning for integrating processes with time delay, is to extend the control and tuning method presented in [15] for the control of IPDT processes, to the case of FOLIPDT processes. In particular, the "pseudo-derivative feedback" (PDF) controller configuration, first proposed in [16], is investigated here as an alternative means of tuning simple two and three controllers for FOLIPDT processes, with enhanced set-point tracking capabilities. Two alternative methods for tuning PD-0F and PD-1F controllers for FOLIPDT processes are proposed in the paper. Similarly to the IPDT process case, the first set of the proposed PD-0F and PD-1F tuning rules relies on accurate approximations of the delay term through first order Taylor and Padé expansions, respectively, and of the crossover frequency of the Nyquist plot of the loop transfer function. The second sets of the proposed PD-0F and PD-1F controller settings, relies on the approximation of the delay term through first order Taylor expansion and on an alternative more accurate approximation of the crossover frequency. The tuning rules are expressed in terms of adjustable parameters, which can be appropriately selected, either to achieve a desired damping ratio for the closed-loop system or to ensure the minimization of classical integral criteria, such as the integral of squared error (ISE) criterion, the integral of squared error plus normalized square controller output deviation (ISENSCOD) criterion [17], and the integral of squared error plus the normalized squared derivative of the controller output (ISENDCO) criterion, for either set-point tracking or regula-

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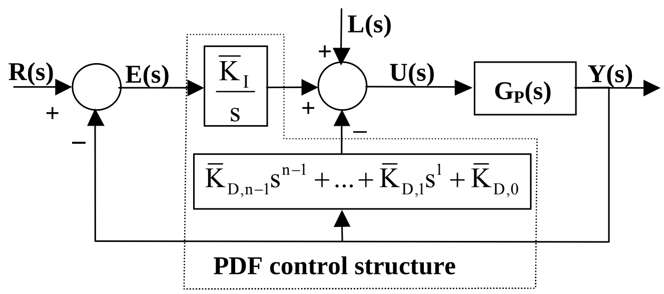

Fig. 1. The general PDF control structure.

tory control. It is worth noticing that, in contrast to the case of IPDT models, here the adjustable parameters minimizing integral criteria are functions of the ratio of the process time delay and the process time constant.

A variety of simulation studies have been performed in the paper and the performance of the proposed methods is compared to that of known PI/PID controller tuning methods for FOLIPDT processes. The obtained results are rather satisfactory. In contrast to known conventional PI/PID tuning rules that result on large overshoot in the closed-loop response, the proposed controller structures and tuning methods ensure smooth response and satisfactory robustness against parametric uncertainty. This enhanced performance is plausible without the need for setpoint weighting or the introduction of set point filters. The comparison also reveals that the proposed methods provide fast attenuation of step load disturbances, in addition to enhanced closed-loop response to set-point changes. Overall, the results of the present paper, together with its companions [15] and [18] provide the means for a rather simple and effective design of two and three term controllers for integrating/time delay processes.

II. FOLIPDT Processes and the PDF Controller Structure

First order lag plus integral plus dead time (FOLIPDT) processes are described by the following transfer function model

$$G_P(s)=G_{P0}(s)exp(-ds)\hat{=}\frac{K}{s(Ts+1)}exp(-ds) \tag{1}$$

where K, T and d are the process gain, time-constant and time delay, respectively. The magnitude and the argument of the FOLIPDT model are given by

$$arg\big(G_P(j\omega)\big)=-\frac{\pi}{2}-d\omega-tan^{-1}(T\omega) \tag{2a}$$

$$\left|G_P(j\omega)\right|=\frac{K}{\omega\sqrt{1+(T\omega)^2}} \tag{2b}$$

The PD-0F and the PD-1F controllers are special cases of the general PDF control structure, depicted in Fig. 1. More precisely, the PD-0F controller corresponds to the case where $K_{D,i}$=0, for i=1,… ,n-1 and $K_{D,0}\equiv K_P\neq 0$, while the PD-1F controller corresponds to the case where $K_{D,0}\equiv K_P\neq 0$, $K_{D,1}=K_d\neq 0$ and $K_{D,i}$=0, for i=2,…,n-1. As it has been shown in [15], the PD-0F controller is equivalent to a standard PI controller with set-point filter of the form $1/(\theta s+1)$, with

$$\theta=K_P/K_I \tag{3}$$

while the PD-1F controller is equivalent to a standard PID controller with set-point filter of the form $1/(\delta\theta s^2+\theta s+1)$, with

$$\delta=K_d/K_p \tag{4}$$

Taking into account this equivalence, the loop transfer function of a FOLIPDT system controlled by a PD-0F controller is given by

$$G_{CL}(s)=\frac{KG_{P0}(s)exp(-ds)}{s+\left(K_Ps+K_I\right)G_{P0}(s)exp(-ds)} =\frac{\frac{KK_I}{Ts+1}exp(-ds)}{s^2+\left(K_Ps+K_I\right)\frac{K}{Ts+1}exp(-ds)} \tag{5}$$

Similarly, the loop transfer function of a FOLIPDT system controlled by a PD-1F controller is given by

$$G_{CL}(s)=\frac{KG_{P0}(s)exp(-ds)}{s+\left(K_ds^2+K_Ps+K_I\right)G_{P0}(s)exp(-ds)} =\frac{\frac{KK_I}{Ts+1}exp(-ds)}{s^2+\left(K_ds^2+K_Ps+K_I\right)\frac{K}{Ts+1}exp(-ds)} \tag{6}$$

III. PD-0F And PD-1F Controller Tuning for FOLIPDT Processes

Solving the equation $arg(G_p(j\omega_u))=-\pi$, we take

$$tan^{-1}(T\omega_u)=\frac{\pi}{2}-d\omega_u \tag{7}$$

Equation (7) is obviously nonlinear and has no analytic solution. Since the calculation of ω_u is important for the derivation of rules for PD-0F controller tuning of FOLIPDT processes, we next apply the approximation $tan^{-1}(x)\approx x$ in (7). Solving the resulting equation yields

$$\omega_u\approx\frac{\pi}{2\hat{d}}\ ,\ \hat{d}=d+T \tag{8}$$

For small values of T, the approximation

$$Ts+1\approx exp(Ts) \tag{9}$$

is next used in (5) to obtain

$$G_{CL}(s) \approx \frac{KK_I\, exp(-\hat{d}s)}{s^2 + K\left(K_P s + K_I\right)exp(-\hat{d}s)} \tag{10}$$

Using the same argument in the case of a PD-1F controller, we obtain the relation

$$G_{CL}(s) \approx \frac{KK_I\, exp(-\hat{d}s)}{s^2 + K\left(K_d s^2 + K_P s + K_I\right)exp(-\hat{d}s)} \tag{11}$$

Clearly, with these manipulations, relations (10) and (11) resemble to relations (4) and (7) reported in [15]. Since (8) also resembles to relation (2b) reported in [15], it is obvious that the problem of controller tuning for FOLIPDT processes with dead-time d, reduces to that of controller tuning for IPDT processes with an augmented time delay $\hat{d}$. Therefore, one can apply the methods presented in [15], in order to obtain the following settings for PD-0F and PD-1F controllers in the case of FOLIPDT processes:

PD-0F Controller Settings for FOLIPDT models

The PD-0F controller settings are selected as

$$K_P = \frac{4}{\left(8-\hat{\beta}\right)\hat{d}K} \quad , \quad K_I = \frac{\hat{\beta}}{\left(8-\hat{\beta}\right)\hat{d}^2 K} \tag{12}$$

where $\hat{\beta}$ is an adjustable parameter, which can be chosen as

$$\hat{\beta} = \frac{4}{4\hat{\zeta}^2_{des} + 1} \tag{13}$$

in order to obtain a desired damping ratio $\hat{\zeta}_{des}$ for the second order approximation of (10), having the form

$$G_{CL}(s) \approx \frac{exp\left(-ds\right)}{\hat{\lambda}^2 s^2 + 2\hat{\zeta}\hat{\lambda}s + 1} \tag{14}$$

$$\hat{\lambda} = \sqrt{\left(K^{-1} - \hat{d}K_P\right)K_I^{-1}} \; , \hat{\zeta} = \frac{K_P K_I^{-1} - \hat{d}}{2\sqrt{\left(K^{-1} - \hat{d}K_P\right)K_I^{-1}}} \tag{15}$$

Alternative PD-0F controller settings can be obtained from the minimization of integral criteria. However, in contrast to what happens in the case of IPDT models, in the case of FOLIPDT processes, the optimal values of the parameter $\hat{\beta}$ minimizing these integrals are not fixed. They depend on the dimensionless parameter $u=d/T$, and they can be easily obtained using simple optimization algorithms. Due to space limitations, we do not present here the optimal values of the adjustable parameter $\hat{\beta}$ and the minima of the integral criteria. We only present, in Table I of the Appendix, some simple estimates of the functions $\hat{\beta}\,(u)$, which have been obtained by fitting their optimal values.

PD-1F Controller Settings for FOLIPDT models

The PD-1F controller settings are selected as

$$K_P = \frac{16}{(16-3\hat{\gamma})\hat{d}K} \tag{16a}$$

$$K_I = \frac{4\hat{\gamma}}{(16-3\hat{\gamma})\hat{d}^2 K} \tag{16b}$$

$$K_d = \frac{8-\hat{\gamma}}{(16-3\hat{\gamma})K} \tag{16c}$$

where $\hat{\gamma}$ is an adjustable parameter, which can be chosen as

$$\hat{\gamma} = \frac{4}{2\hat{\xi}^2_{des} + 1} \tag{17}$$

in order to obtain a desired damping ratio $\hat{\xi}_{des}$ for the second order approximation of (11), having the form

$$G_{CL}(s) \approx \frac{exp(-\hat{d}s)}{\hat{\rho}^2 s^2 + 2\hat{\xi}\hat{\rho}s + 1} \tag{18}$$

$$\hat{\rho} = \sqrt{\frac{1}{KK_I} - \frac{\hat{d}K_P}{2K_I} + \frac{\hat{d}^2}{4}} \; , \; \hat{\xi} = \frac{\dfrac{K_P}{K_I} - \hat{d}}{2\sqrt{\dfrac{1}{KK_I} - \dfrac{\hat{d}K_P}{2K_I} + \dfrac{\hat{d}^2}{4}}}$$

Alternative PD-0F controller settings can be obtained from the minimization of integral criteria. Table II of the Appendix, summarizes some simple estimates of the functions $\hat{\gamma}\,(u)$, which minimize some of these integrals and which have been obtained by fitting the optimal values of the adjustable parameters, given by optimization algorithms.

Approximation (9) is of course valid for small values of T or s, while, for large values of T, the actual closed-loop system may differ from those given by relations (14) or (18). However, as it can be easily seen by simulation, relations (12) and (16) provide acceptable PD-0F or PD-1F settings even for large values of T. A way to obtain a more satisfactory closed-loop performance is the following:

Rewrite (7) in the form

$$T\omega_u = tan\left(\frac{\pi}{2} - d\omega_u\right) \tag{19}$$

and use the following approximation for the *tan* function

$$tan(x) \approx x + x^2[\pi(0.5\pi - x)]^{-1} \tag{20}$$

Using (20) in (19) yields

$$4d\left(d+T-\pi^{-1}\right)\omega_u^2-4d\left(0.5\pi-1\right)\omega_u-\pi=0$$

The solution of the above equation is given by

$$\omega_u \approx \frac{0.5\pi-1}{2(d+T-\pi^{-1})}\left[1+\sqrt{1+\frac{\pi(d+T-\pi^{-1})}{d\left(0.5\pi-1\right)^2}}\right] \tag{21}$$

Equation (21) provides a very accurate estimation of the crossover frequency.

Observe now that equation (6) can alternatively be written as

$$G_{CL}(s)=\frac{\dfrac{KK_I}{Ts+1}exp(-ds)}{s^2+\left(KK_dT^{-1}s+\left(KK_PT^{-1}-KK_dT^{-2}\right)+P(s)\right)exp(-ds)}$$

where

$$P(s)=\frac{KK_I+KK_dT^{-2}-K_PT^{-1}}{Ts+1}$$

Observe now that if K_d is selected as

$$K_d=TK_P-T^2K_I \tag{22}$$

then $P(s)=0$ and $KK_PT^{-1}-KK_dT^{-2}=KK_I$. Therefore,

$$G_{CL}(s)=\frac{\dfrac{KK_I}{Ts+1}exp(-ds)}{s^2+\left[K\left(K_P-TK_I\right)s+KK_I\right]exp(-ds)} \tag{23}$$

Using the approximation (9) in the numerator of (23), and the approximation $exp(-ds)\approx 1-ds$ in its denominator, yields

$$G_{CL}(s)\approx\frac{KK_I\,exp\left(-\hat{d}s\right)}{s^2+\left[K\left(K_P-TK_I\right)s+KK_I\right](1-ds)}$$

After some easy manipulations, the above equation can be written as

$$G_{CL}(s)\approx\frac{exp\left(-\hat{d}s\right)}{\sigma^2s^2+2\eta\sigma s+1} \tag{24}$$

$$\sigma=\sqrt{K^{-1}K_I^{-1}-d\left(K_PK_I^{-1}-T\right)}=\sqrt{\theta K^{-1}K_P^{-1}-d\left(\theta-T\right)}$$

$$\eta=\frac{K_PK_I^{-1}-d-T}{2\sqrt{K^{-1}K_I^{-1}-d\left(K_PK_I^{-1}-T\right)}}=\frac{\theta-d-T}{2\sqrt{\theta K^{-1}K_P^{-1}-d\left(\theta-T\right)}}$$

Simulation results show that this kind of manipulation, leads to controller settings, which are more satisfactory in the case of large values of T, and they offer more acceptable closed-loop performance.

The Routh stability conditions about equation (24) yield

$$(d+T)K_I<K_P<d^{-1}K^{-1}+TK_I \tag{25}$$

provided that $K_I<1/(d^2K)$. Clearly, inequality (25) provides the admissible range of the PD-1F controller parameter K_P.

We are now able to present a method for tuning the PD-1F controller parameters in the present case. The proposed method is as follows:

2nd PD-1F Controller Tuning Method for FOLIPDT models

As for K_P, we choose the middle value of the allowed range given by the inequality (25). That is

$$K_P=\frac{d^{-1}K^{-1}+(d+2T)K_I}{2} \tag{26}$$

or, by using (3),

$$K_P=\frac{\theta}{\left(2\theta-d-2T\right)dK} \tag{27}$$

If θ is specified, then, the PD-1F controller settings can be obtained from (27), (3) and (22). Here, as for θ, it is proposed to choose

$$\theta=\frac{2\pi}{\omega_u\gamma_1} \tag{28}$$

where ω_u is given by (21) and γ_1 is an adjustable parameter. With this choice, we obtain

$$\theta=\frac{x_1}{x_2\gamma_1} \tag{29a}$$

$$x_1=4\pi(d+T-\pi^{-1}) \tag{29b}$$

$$x_2=(0.5\pi-1)\left[1+\sqrt{1+\frac{\pi(d+T-\pi^{-1})}{d\left(0.5\pi-1\right)^2}}\right] \tag{29c}$$

and

$$K_P=\frac{x_1}{\left[2x_1-\left(d+2T\right)x_2\gamma_1\right]dK} \tag{30a}$$

$$K_I=\frac{x_2\gamma_1}{\left[2x_1-\left(d+2T\right)x_2\gamma_1\right]dK} \tag{30b}$$

$$K_d=\frac{Tx_1-T^2x_2\gamma_1}{\left[2x_1-\left(d+2T\right)x_2\gamma_1\right]dK} \tag{30c}$$

The adjustable parameter γ_1 can be selected appropriately in order to satisfy several design specifications for the closed-loop system. As in the case of IPDT processes, parameter γ_1 can be selected in such a way that a desired damping ratio η_{des} is obtained for the second order approximation (24). In this case, γ_1 must be the minimum real root of the quadratic equation

$$(d+T)\left(d+T+4d\eta_{des}^2\right)x_2^2\gamma_1^2-2\left(d+T+2d\eta_{des}^2\right)x_1x_2\gamma_1+x_1^2=0 \quad (31)$$

For the present method, alternative PD-1F controller settings can be obtained from the minimization of integral criteria. Table III in the Appendix summarizes some simple estimates of the functions $\gamma_1(u)$, which minimize these integrals and which have been obtained by fitting the optimal values of the adjustable parameters, given by optimization algorithms.

Now, returning to the problem of tuning PD-0F controllers, observe that equation (5) takes the form

$$G_{CL}(s)=\frac{\dfrac{KK_I}{Ts+1}exp(-ds)}{s^2+F(s)} \quad (32)$$

where

$$F(s)=\left(K_Ps+K_I\right)\frac{K}{Ts+1}exp(-ds) \quad (33)$$

Expanding $F(s)$ in Mclaurin series and taking the second order approximation, we obtain

$$\begin{aligned}F(s)&\approx KK_I+\left[KK_P-(d+T)KK_I\right]s\\&+\left[-(d+T)KK_P+\left(\frac{d^2}{2}+dT+T^2\right)KK_I\right]s^2\end{aligned} \quad (34)$$

Substituting (33) in (32) and taking into account (9), we finally obtain

$$G_{CL}(s)\approx\frac{KK_I\,exp\left(-\hat{d}s\right)}{A_2s^2+A_1s+A_0}$$

$$A_2=1-(d+T)KK_P+\left(\frac{d^2}{2}+dT+T^2\right)KK_I$$

$$A_1=KK_P-(d+T)KK_I \quad , \quad A_0=KK_I$$

or equivalently

$$G_{CL}(s)\approx\frac{exp(-\hat{d}s)}{\tilde{\lambda}^2s^2+2\tilde{\zeta}\tilde{\lambda}s+1} \quad (34a)$$

$$\tilde{\lambda}=\sqrt{\frac{1}{KK_I}-(d+T)\frac{K_P}{K_I}+\frac{d^2}{2}+dT+T^2} \quad (34b)$$

$$\tilde{\zeta}=\frac{\dfrac{K_P}{K_I}-(d+T)}{2\sqrt{\dfrac{1}{KK_I}-(d+T)\dfrac{K_P}{K_I}+\dfrac{d^2}{2}+dT+T^2}} \quad (34c)$$

The Routh stability conditions about equation (34) yield

$$(d+T)K_I<K_P<\frac{1}{(d+T)K}+\frac{\left(\dfrac{d^2}{2}+dT+T^2\right)K_I}{d+T} \quad (35)$$

We next present an alternative method for tuning the PD-0F controller in the case of FOLIPDT processes. The proposed method is as follows:

2nd PD-0F Controller Tuning Method for FOLIPDT models

As for K_P, we choose the middle value of the allowed range given by the inequality (35). That is

$$K_P=\frac{1}{2(d+T)K}+\frac{\left(\dfrac{3}{2}d^2+3dT+2T^2\right)K_I}{2(d+T)} \quad (36)$$

or, by using (3),

$$K_P=\frac{\theta}{\left[2(d+T)\theta-\left(\dfrac{3}{2}d^2+3dT+2T^2\right)\right]K} \quad (37)$$

It is now proposed to choose θ, according to the following relation

$$\theta=\frac{x_1}{x_2\gamma_2} \quad (38)$$

where γ_2 is an adjustable parameter and where x_1 and x_2 are given by (29b) and (29c). With this choice, we obtain the following settings for the PD-0F controller parameters

$$K_P=\frac{x_1}{\left[2(d+T)x_1-\left(\dfrac{3}{2}d^2+3dT+2T^2\right)x_2\gamma_2\right]K} \quad (39a)$$

$$K_I=\frac{x_2\gamma_2}{\left[2(d+T)x_1-\left(\dfrac{3}{2}d^2+3dT+2T^2\right)x_2\gamma_2\right]K} \quad (39b)$$

The adjustable parameter γ_2 can be selected appropriately in order to satisfy several design specifications for the closed-loop system. As in the case of IPDT processes, parameter γ_2 can be selected in such a way that a desired damping ratio $\tilde{\zeta}_{des}$ is obtained for the second order approximation (34). In this case, γ_2 must be the minimum real root of the quadratic equation

$$(d+T)^2(1+4\tilde{\zeta}_{des}^2)x_2^2\gamma_2^2-2(d+T)\left(1+2\tilde{\zeta}_{des}^2\right)x_1x_2\gamma_2+x_1^2=0 \quad (40)$$

For the present method, alternative PD-0F controller set-

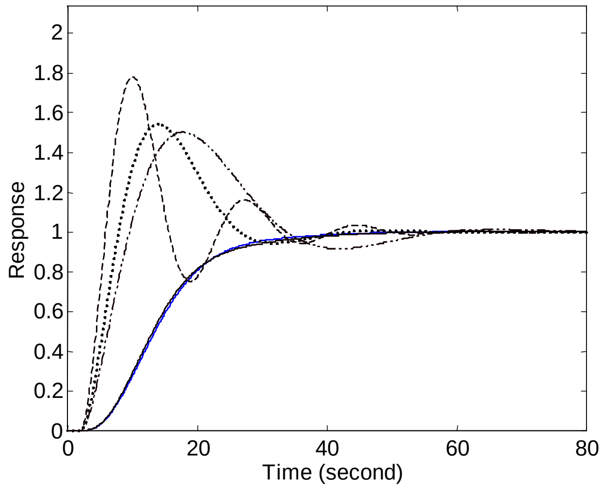

Fig. 2a. Servo response for different methods for PI and PD-0F controller tuning, without the use of setpoint filters. Solid-black: first proposed method ($\hat{\beta}$=0.8); solid-blue: second proposed method (γ_2=0.8317); dot: S-method-I; dash: S-method-II; dash-dot: M-method.

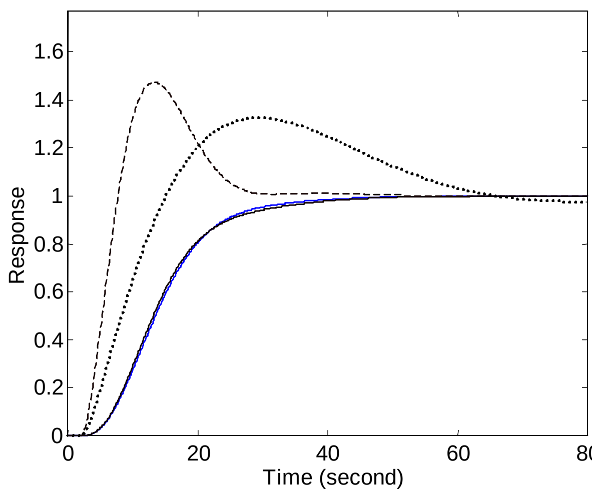

Fig. 2b. Servo response for different methods for PI and PD-0F controller tuning, without the use of setpoint filters. Solid-black: first proposed method ($\hat{\beta}$=0.8); solid-blue: second proposed method (γ_2=0.8317); dash: P-P method; dot: A-H method.

tings can be obtained from the minimization of integral criteria. Table IV summarizes some simple estimates of the functions $\gamma_2(u)$, which minimize these integrals and which have been obtained by fitting the optimal values of the adjustable parameters, given by optimization algorithms.

IV. Simulation Studies

In order to demonstrate the effectiveness of the proposed control structure and tuning methods for FOLIPDT processes and to provide a comparison with existing tuning formulas for conventional PI/ PID controller tuning, a numerical example is elaborated in this section. In this example, the FOLIPDT model parameters are K=1, T=1, d=2.

We first proceed with a comparison of the proposed me-

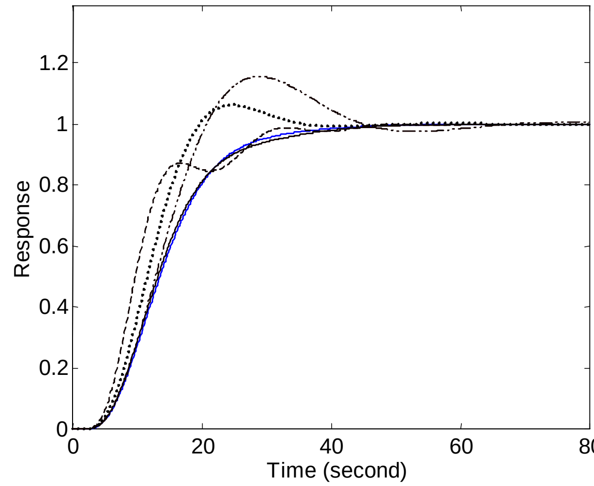

Fig. 2c. Legend as in Fig. 2a, but, now, with a setpoint filter of the form $1/(\theta s+1)$ added in the PI controller configuration.

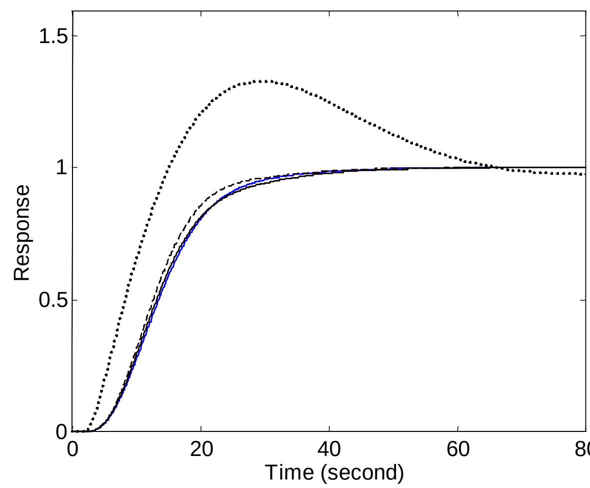

Fig. 2d. Legend as in Fig. 2b, but, now, with a setpoint filter of the form $1/(\theta s+1)$ added in the PI controller configuration, when the P-P method is applied.

thods for PD-0F controller tuning with the methods for PI controller tuning reported in [9] (M-method), [10] (S-method), [11] (P-P method) and [5] (A-H method). The PI controller settings given by the M-method are K_P=0.1377, θ=10.8715. S-method provides the settings K_P=0.1853, θ=11.1 (S-method-I) and K_P=0.3173, θ=12 (S-method-II) (see [6] for details). The settings obtained from the application of the P-P method are K_P=0.1991, θ=14.0007, while the A-H method yields K_P= 0.1182, θ=26.0568. The servo responses obtained by applying the M-method as well as the settings given by S-method-I and S-method-II are shown in Fig. 2a. The performance of the proposed controller, whose settings are given by relations (12) and (13) for $\hat{\zeta}_{des}=1$ ($\hat{\beta}$=0.8) as K_P=0.1852, K_I=0.0123 and by relations (39a), (39b), (40), for $\tilde{\zeta}_{des}=1$ (γ_2=0.8317) as K_P= 0.1974, K_I=0.0132, are also given in Fig. 2a. Fig. 2b illustrates the servo responses obtained by the application of the P-P method and the A-H method together with those obtained by the proposed PD-0F controller structure and tuning method. From

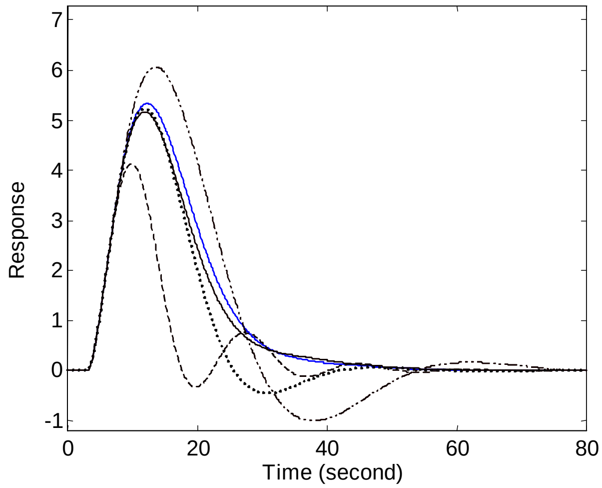

Fig. 2e. Regulatory response for different methods for PI and PD-0F controller tuning. Other legend as in Fig. 2a.

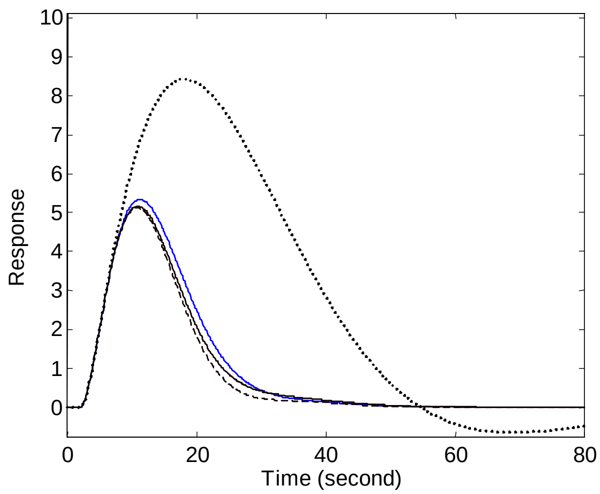

Fig. 2f. Regulatory response for different methods for PI and PD-0F controller tuning. Other legend as in Fig. 2b.

the above figures, it becomes clear that, with the exception of the A-H method, all conventional PI controller tuning methods give large overshoots, exceeding 50%. Moreover, the S-method-II yields an oscillatory response. The A-H method yields the smallest overshoot among the conventional PI controller tuning methods, but the settling time obtained is quite large. Our method is the best in terms of both overshoot and settling time.

As already mentioned above, the proposed PD-0F controller is equivalent to a PI controller with a set-point filter. Therefore, it is fair to perform a comparison of the proposed PD-0F controller tuning methods with the abovementioned PI controller tuning methods, in the case where a set point filter of the form *1/(θs+1)*, although not suggested in [9]-[11], is added, in order to implement the control loop. Note that, in the sequel, no setpoint filter is used when the A-H method is applied, because this method relies on setpoint weighting, which is used instead of a set point filter. Figs. 2c and 2d, illustrate the servo responses obtained by the application of the

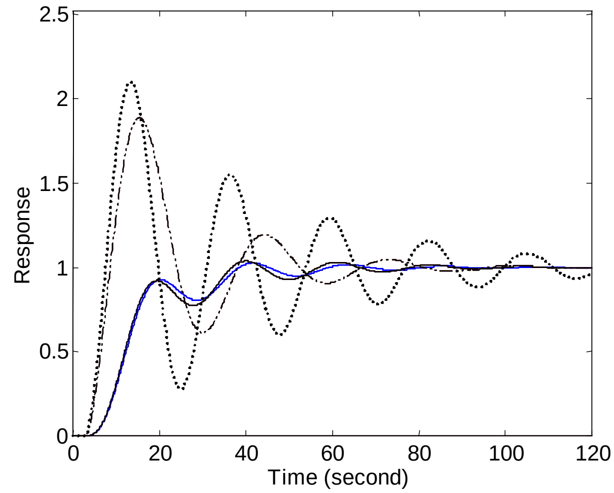

Fig. 2g. Servo response under simultaneous parametric uncertainty. K=1, T=1, d=2 for controller design and K=1.4, T=1.4, d=2.8 in the process. Other legend as in Fig. 2a. S-method-II gives unstable response.

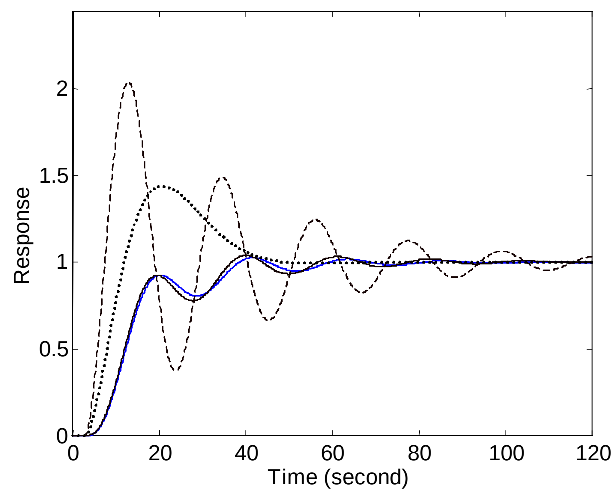

Fig. 2h. Servo response under simultaneous parametric uncertainty. K=1, T=1, d=2 for controller design and K=1.4, T=1.4, d=2.8 in the process. Other legend as in Fig. 2b.

methods under comparison. Our methods give smaller overshoot, as compared to the M-method or the S-method-II, and give as fast response as the S-method-I and the P-P method. Finally, our methods are significantly better than the A-H method in terms of both overshoot and settling time.

We next perform a comparison of the proposed PD-0F controller tuning methods with the conventional PI controller tuning methods mentioned above, in the case of regulatory control. The regulatory responses obtained by applying the M-method and the S-method, are shown in Fig. 2e. Figure 2f illustrates the regulatory responses obtained by applying the P-P method and the A-H method. A unit step load change is assumed. The performance of the proposed PD-0F controller, whose settings are as in the case of servo control, is also given in Figs. 2e and 2f. From these figures, it becomes clear that the smallest error is provided by the S-method-II. Both the M-method and the A-H method provide poor regulatory control, since their responses present large error and settling time. For

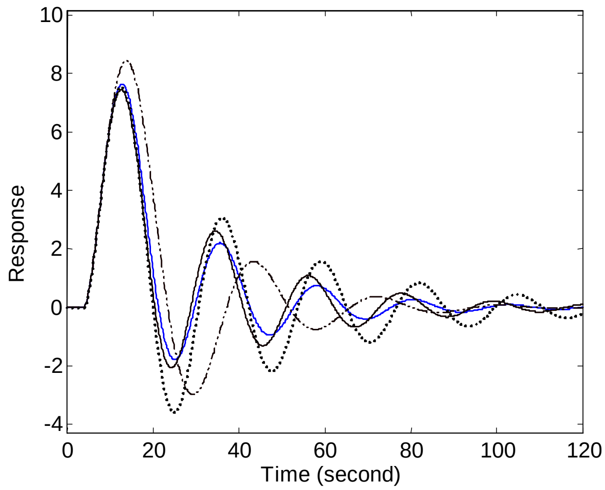

Fig. 2i. Regulatory response under simultaneous parametric uncertainty. Other legend as in Fig. 2g.

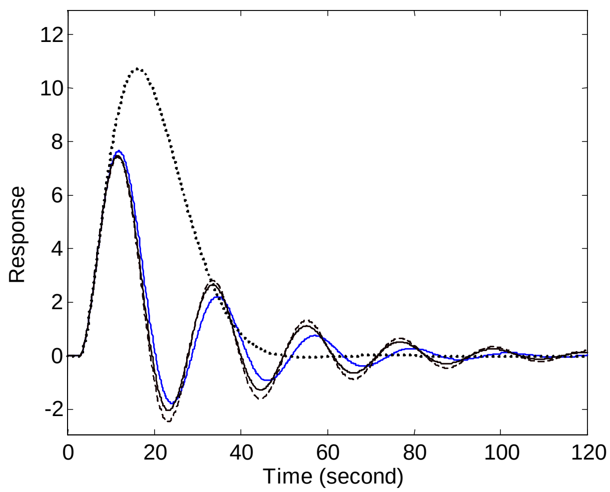

Fig. 2j. Regulatory response under simultaneous parametric uncertainty. Other legend as in Fig. 2h.

regulatory control, our method is comparable to the S-method-I and the P-P method, in terms of maximum error and settling time. In particular, the proposed control and tuning method gives results almost identical to those obtained from the application of the P-P method for PI controller tuning.

The robustness of the proposed PD-0F controller tuning methods is studied by using a 40% simultaneous perturbation in K, T and d from their nominal values in the simulation (K=1.4, T=1.4, d=2.8), whereas the controller settings are those calculated for the process with nominal parameters (K=1, T=1, d= 2). Figs. 2g and 2h illustrate the servo responses. The responses are obtained for the regulatory problem as shown in Figs. 2i and 2j. Note that, with this simultaneous uncertainty, the S-method-II gives unstable responses for both servo and regulatory control. It becomes obvious from Figs. 2g-2j that with the exception of the A-H method, the first proposed PD-0F controller tuning methods give the best robust performance, in terms of both overshoot and settling time. The A-H method gives smaller settling time, but larger overshoot, as compared

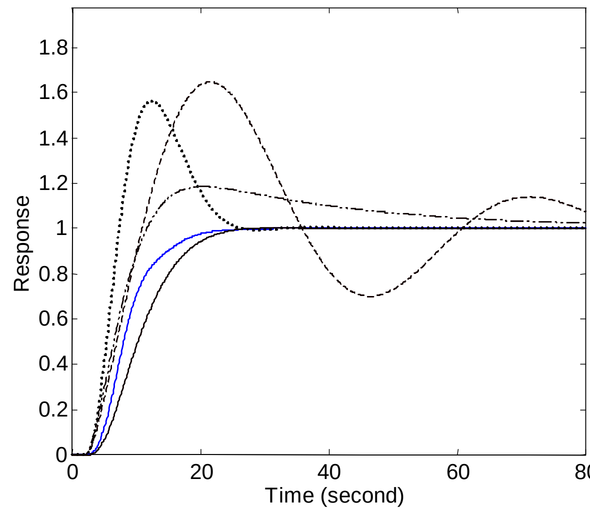

Fig. 3a. Servo response for different methods for PID and PD-1F controller tuning, without the use of setpoint filters. Solid-black: first proposed method ($\hat{\gamma}$ =1.3333); solid-blue: second proposed method (γ_I=1.1342); dash: M-method; dot: Z-X-S-method; dash-dot: A-H method.

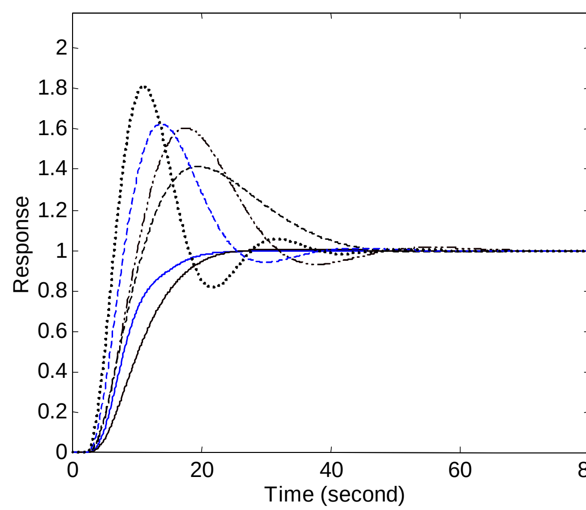

Fig. 3b. Servo response for different methods for PID and PD-1F controller tuning, without the use of setpoint filters. Solid-black: first proposed method ($\hat{\gamma}$ =1.3333); solid-blue: second proposed method (γ_I=1.1342); dash-black: T-L-S method-I; dash-blue: T-L-S method II; dot: T-L-S-method-III; dash-dot: T-L-T method.

to our methods.

We next perform a comparison of the proposed methods for PD-1F controller tuning of FOLIPDT processes with the methods for PID controller tuning reported in [5], [9], [12]-[14] For the FOLIPDT model with parameter values K=1, T=1 and d=2, the PID settings given by the method in [9] (M-method) are K_P=0.1036, θ=6.5491, δ=1.6373. The A-H method [5] provides the settings K_P=0.1086, θ=27.1009, δ=0.1160 and the setpoint weighting parameter b=0.6353. The T-L-T method [12] gives K_P= 0.1735, θ=14.624, δ=0.9316 and the derivative filter time constant T_f=1.7167. The T-L-S method [13] provides the settings K_P=0.146, θ=17.3266, δ=0.9423, T_f=1.1098 (T-L-S-method-I), K_P=0.2212, θ=11.7354 δ=0.9148, T_f=

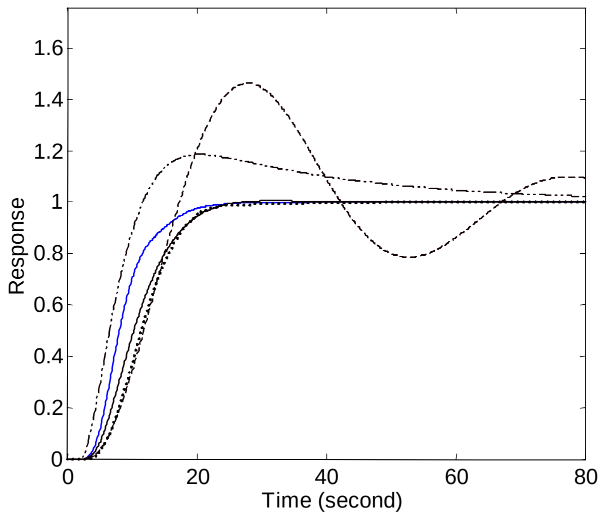

Fig. 3c. Legend as in Fig. 3a, but, now, with a setpoint filter of the form $1/(\delta\theta s^2+\theta s+1)$ added in the PI controller configuration, when the M-method and the Z-X-S method are applied.

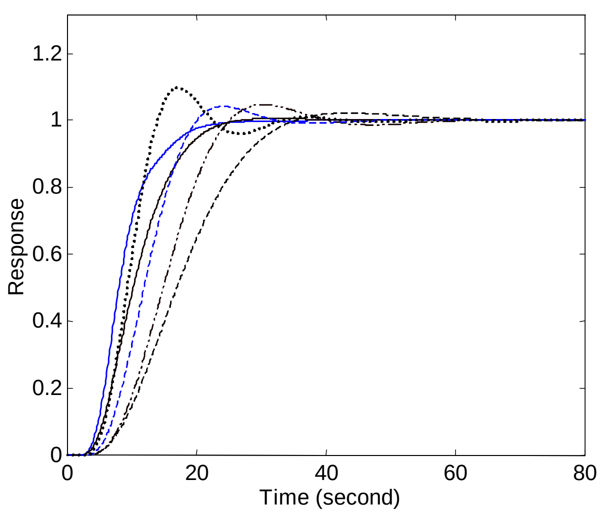

Fig. 3d. Legend as in Fig. 3b, but, now, with a setpoint filter of the form $1/(\delta\theta s^2+\theta s+1)$ added in the PI controller configuration.

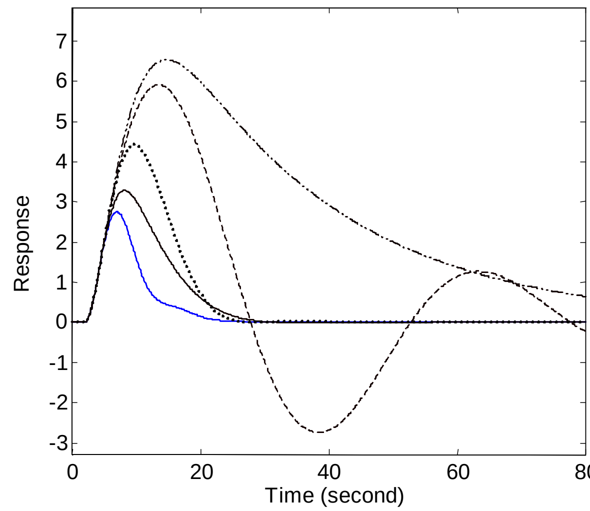

Fig. 3e. Regulatory response for different methods for PID and PD-1F controller tuning. Other legend as in Fig. 3a.

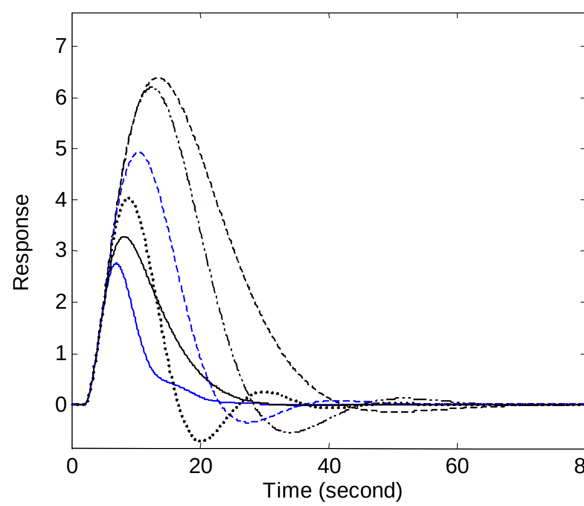

Fig. 3f. Regulatory response for different methods for PID and PD-1F controller tuning. Other legend as in Fig. 3b.

0.8964 (T-L-S-method-II) and K_P=0.2999, θ=8.927, δ=0.888, T_f=0.5726. Finally, the Z-X-S method [14] provides the PID settings K_P=0.2449, θ=12, δ=0.9167, T_f=0.551. The servo responses obtained by applying the M-method, the Z-X-S method and the A-H method, are shown in Fig. 3a. The performance of the proposed controller, whose settings are given by relations (16a)-(1c) for $\hat{\gamma}$=1.3333 ($\hat{\xi}_{des}$=1) as K_P=0.4444, K_I= 0.0494, K_d= 0.5556 and for γ_I=1.1342 ($\tilde{\xi}_{des}$=1) as K_P=0.3056, K_I=0.0278, K_d=0.3951, is also given in Fig. 3a. Fig. 3b illustrates the servo responses obtained by the application of the T-L-T method and the T-L-S method I-III together with those obtained by the proposed PD-1F controller tuning methods. It is noted that no set-point filter is used in order to implement the PID controller loop. Clearly, all known PID tuning methods except the A-H method give excessive overshoot. Moreover, the M-method gives an oscillatory response with large settling time. The A-H method provides less overshoot (only 20%), but it is the worst in terms of settling time. The proposed PD-1F controller tuning methods provides smooth response and small settling time. Figs. 3c and 3d illustrate the servo responses obtained by the applying the above PID tuning methods and the proposed PD-1F controller tuning methods, in the case where a set-point filter of the form $1/(\delta\theta s^2+\theta s+1)$ is used in the PID control configuration, to reduce the overshoot. Note that, no setpoint filter is used when the A-H method is applied, because this method relies on setpoint weighting, which is used instead of a set point filter. Even in this case the proposed methods give smoother responses with satisfactory settling times. In particular, the proposed PD-1F controller tuning methods give servo responses almost identical to that obtained from the application of the Z-X-L method for PID controller tuning.

The performance of the proposed PD-1F controller tuning methods and of the conventional PID controller tuning me-

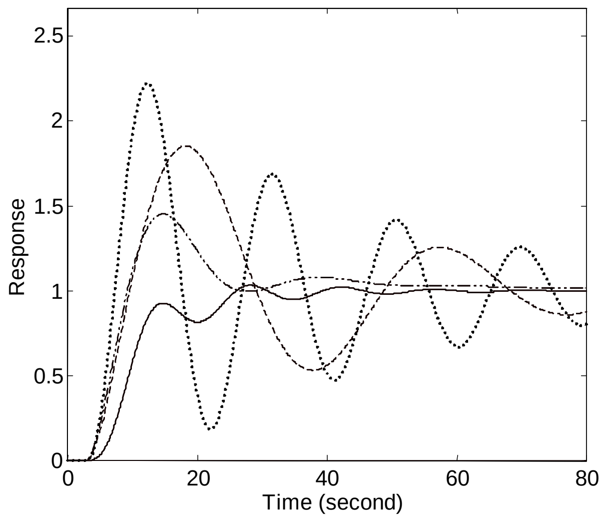

Fig. 3g. Servo response under simultaneous parametric uncertainty. K=1, T=1, d=2 for controller design and K=1.4, T=1.4, d=2.8 in the process. Other legend as in Fig. 3a. The second proposed method gives an unstable response.

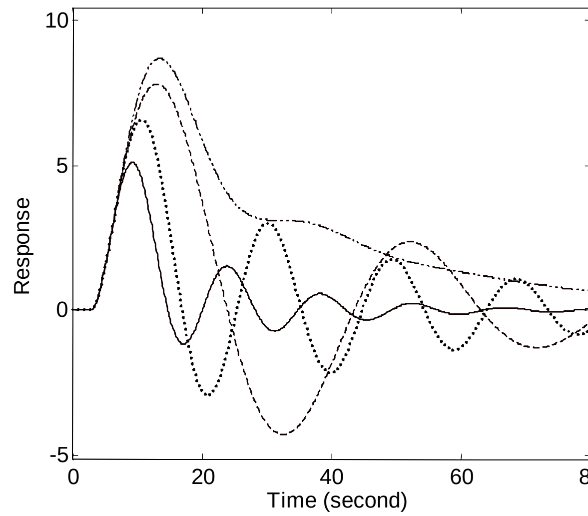

Fig. 3i. Regulatory response under simultaneous parametric uncertainty. Other legend as in Fig. 3g.

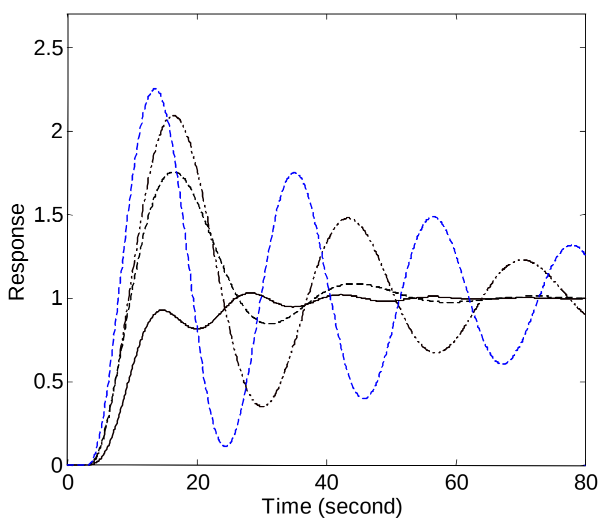

Fig. 3h. Servo response under simultaneous parametric uncertainty. K=1, T=1, d=2 for controller design and K=1.4, T=1.4, d=2.8 in the process. Other legend as in Fig. 3b. The second proposed method and T-L-S-method-III give unstable responses.

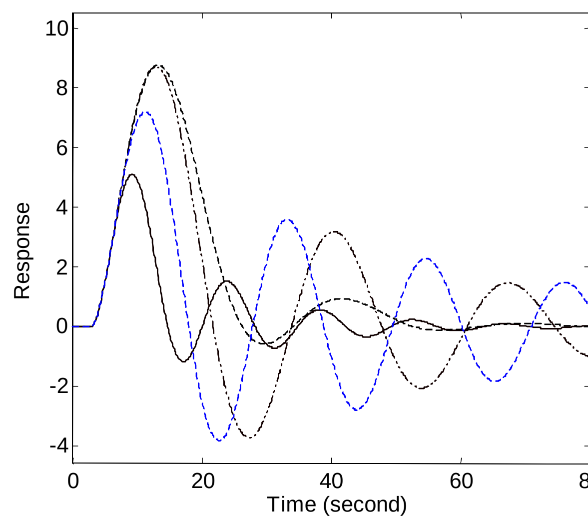

Fig. 3j. Regulatory response under simultaneous parametric uncertainty. Other legend as in Fig. 3h.

thods mentioned above, in the case of regulatory control, is illustrated in Figures 3e and 3f. In the comparison, a unit step load change is assumed. From these figures, it becomes clear that both the M-method and the A-H method provide poor regulatory control, since their responses present large error and settling time. The smallest error is provided by the proposed PD-1F controller tuning methods, which are the best in the case of regulatory control of FOLIPDT processes.

The robustness of the proposed PD-1F controller tuning methods is studied by using a 40% simultaneous perturbation in K, T and d from their nominal values in the simulation (K= 1.4, T=1.4, d=2.8), whereas the controller settings are those calculated for the process with nominal parameters (K=1, T=1, d=2). Figs. 3g and 3h illustrate the servo responses. The responses are obtained for the regulatory problem as shown in Figs. 3i and 3j. Note that, with the assumed simultaneous parametric uncertainty both the second proposed PD-1F controller tuning method and the T-L-S-method-III give unstable responses for both servo and regulatory control. It becomes obvious from Figs. 3g-3j that the first proposed PD-1F controller tuning method gives the best robust performance, in terms of both overshoot and settling time.

V. Conclusions

In the third part of the present paper, simple methods for tuning PD-0F and PD-1F controllers for FOLIPDT processes have been proposed. Their performance has been compared with that of conventional PI/PID controller tuning methods. The comparison reveals that the proposed control and tuning methods are superior, as compared to the existing PI/PID tuning methods in both servo and regulatory control problems, while they provide a more robust performance.

Overall, taking into account the present analysis and the results reported in Parts I and II [15], [18], the proposed PDF controller and tuning methods offers better performance and robustness characteristics and give us the opportunity of having a new insight in the problem of designing simple PI/PID-like controllers for integrating processes with time delay.

APPENDIX

The following tables refer to the estimates of the optimal values of the adjustable parameters $\hat{\beta}$, $\hat{\gamma}$, γ_1 and γ_2.

TABLE I
ESTIMATES OF THE OPTIMAL VALUES OF $\hat{\beta}$ FOR VARIOUS INTEGRAL CRITERIA.

Criterion	Estimate of optimal $\hat{\beta}$ *(u)*	Comments
ISE_SP	$1.997-0.82781u+1.0002u^2-0.72106u^3+0.32269u^4-0.092452u^5+0.017215u^6-0.0020706u^7+0.00015505u^8-6.5691\times10^{-6}u^9+1.2025\times10^{-7}u^{10}$	For $0<u<5.5$
ISE_SP	$1.6281745-0.001171(u-5.5)$	For $u\geq5.5$
ISE_L	$2.6302-2.1248u+2.5776u^2-1.8511u^3+0.82557u^4-0.23641u^5+0.044128u^6-0.0053335u^7+0.00040201u^8-1.7164\times10^{-5}u^9+3.1685\times10^{-7}u^{10}$	For $0<u<4.1$
ISE_L	$1.7110073-0.003554(u-4.1)$	For $u\geq4.1$
ISENSCOD_SP	$1.5693+0.1066u-0.10101u^2+0.05217u^3-0.016147u^4+0.0030412u^5-0.00032187u^6+1.2181\times10^{-5}u^7+9.9698\times10^{-7}u^8-1.2274\times10^{-7}u^9+3.7365\times10^{-9}u^{10}$	
ISENSCOD_L	$2.1054-0.76462u+0.79445u^2-0.51826u^3+0.21771u^4-0.06u^5+0.010927u^6-0.0013006u^7+9.717\times10^{-5}u^8-4.132\times10^{-6}u^9+7.6235\times10^{-8}u^{10}$	For $0<u<4.6$
ISENSCOD_L	$1.69667833406-0.00148768(u-4.6)$	For $u\geq4.6$
ISENDCO_SP	$0.780651417+4.7464131(u-0.1)$	For $0<u<0.3$
ISENDCO_SP	$1.729934-0.051535(u-0.3)$	For $0.3\leq u<2$
ISENDCO_L	$1.6505623-0.0034985(u-8)$	For $u\geq2$
ISENDCO_L	$2.1806-0.60273u+0.3875u^2-0.14955u^3+0.034535u^4-0.0042243u^5+8.2395\times10^{-5}u^6+5.0912\times10^{-5}u^7-7.283\times10^{-6}u^8+4.2603\times10^{-7}u^9-9.5824\times10^{-9}u^{10}$	

TABLE II
ESTIMATES OF THE OPTIMAL VALUES OF $\hat{\gamma}$ FOR VARIOUS INTEGRAL CRITERIA.

Criterion	Estimate of optimal $\hat{\gamma}$ *(u)*	Comments
ISE_SP	$1.2171+0.7339u+0.083449u^2-0.14905u^3+0.030257u^4+0.0045567u^5-0.0029943u^6+0.00056821u^7-5.4957\times10^{-5}u^8+2.7505\times10^{-6}u^9-5.6642\times10^{-8}u^{10}$	
ISE_L	$1.5841+0.3101u+0.38841u^2-0.4622u^3+0.21918u^4-0.060691u^5+0.010771u^6-0.0012466u^7+9.1201\times10^{-5}u^8-3.8302\times10^{-6}u^9+7.0316\times10^{-8}u^{10}$	
ISENSCOD_SP	$0.083709+2.2875u-0.18739u^2-1.0059u^3+0.79718u^4-0.3036u^5+0.067859u^6-0.0093104u^7+0.00077161u^8-3.5473\times10^{-5}u^9+6.9487\times10^{-7}u^{10}$	For $0<u<4.5$
ISENSCOD_SP	$2.444547-0.0146274714(u-4.5)$	For $u\geq4.5$
ISENSCOD_L	$0.066485+2.0757u+1.0972u^2-2.7957u^3+1.9019u^4-0.68418u^5+0.14763u^6-0.019733u^7+0.0016016u^8-7.2368\times10^{-5}u^9+1.397\times10^{-6}u^{10}$	For $0<u<4.0$
ISENSCOD_L	$2.128638-0.00560812(u-4)$	For $u\geq4.0$

TABLE III
ESTIMATES OF THE OPTIMAL VALUES OF γ_1 FOR VARIOUS INTEGRAL CRITERIA.

Criterion	Estimate of optimal $\gamma_1(u)$	Comments
ISE_SP	$1.1571+5.0775u-8.2021u^2+6.6353u^3-3.1355u^4+0.92683u^5-0.17635u^6+0.02158u^7-0.0016402u^8+7.0439\times10^{-5}u^9-1.3056\times10^{-6}u^{10}$	For $0<u<4.5$
ISE_SP	$2.124307-0.004844182(u-4.5)$	For $u\geq4.5$
ISE_L	$1.178+4.5663u-7.0371u^2+5.5784u^3-2.6103u^4+0.7679u^5-0.1458u^6+0.017833u^7-0.0013561u^8+5.83\times10^{-5}u^9-1.0823\times10^{-6}u^{10}$	For $0<u<3.5$
ISE_L	$2.2036-0.0033077(u-6.5)$	For $u\geq3.5$
ISENSCOD_SP	$-0.70861+7.4212u-8.1214u^2+4.8168u^3-1.7217u^4+0.38998u^5-0.056975u^6+0.0053141u^7-0.00030233u^8+9.3969\times10^{-6}u^9-1.1861\times10^{-7}u^{10}$	For $0<u<4.5$
ISENSCOD_SP	$2.1069751341-0.0017098(u-4.5)$	For $u\geq4.5$
ISENSCOD_L	$-0.1185+4.781u-3.9977u^2+1.733u^3-0.42245u^4+0.057708u^5-0.0038421u^6+2.6386\times10^{-5}u^7+1.078\times10^{-5}u^8-4.2486\times10^{-7}u^9$	
ISENDCO_SP	$0.05486+0.81662u-1.4989u^2+1.1995u^3-0.48464u^4+0.11011u^5-0.013386u^6+0.00059665u^7+3.8633\times10^{-5}u^8-5.307\times10^{-6}u^9+1.6437\times10^{-7}u^{10}$	For $0<u<6.0$
ISENDCO_SP	$2.1111-0.001025(u-6)$	For $u\geq6.0$

TABLE IV

ESTIMATES OF THE OPTIMAL VALUES OF γ_2 FOR VARIOUS INTEGRAL CRITERIA.

Criterion	Estimate of optimal $\gamma_2(u)$	Comments
ISE_SP	$0.79001+2.114u-2.5601u^2+1.8971u^3-0.86871u^4+0.25371u^5-0.048068u^6+0.0058771u^7-0.00044707u^8+1.9231\times10^{-5}u^9-3.5718\times10^{-7}u^{10}$	For 0<u<4.5
ISE_SP	$1.903177576+0.0181584(u-4.5)$	For u≥4.5
ISE_L	$0.99315+1.9536u-2.5157u^2+1.9163u^3-0.8893u^4+0.26167u^5-0.049809u^6+0.0061098u^7-0.00046593u^8+2.0083\times10^{-5}u^9-3.7368\times10^{-7}u^{10}$	For 0<u<6.0
ISE_L	$1.96705757+0.01308189(u-6)$	For u≥6.0
ISENSCOD_SP	$0.48124+2.5549u-2.896u^2+2.0495u^3-0.91115u^4+0.26094u^5-0.048775u^6+0.0059064u^7-0.00044618u^8+1.9095\times10^{-5}u^9-3.5335\times10^{-7}u^{10}$	For 0<u<4.0
ISENSCOD_SP	$1.87054524+0.021802(u-4)$	For u≥4.0
ISENSCOD_L	$0.73114+2.3461u-2.8509u^2+2.0965u^3-0.95252u^4+0.27639u^5-0.052089u^6+0.0063413u^7-0.00048064u^8+2.0611\times10^{-5}u^9-3.8178\times10^{-7}u^{10}$	For 0<u<4.5
ISENSCOD_L	$1.916423116+0.018175439(u-4.5)$	For u≥4.5
ISENDCO_SP	$0.31373+3.7796u-5.0294u^2+3.8589u^3-1.7956u^4+0.52906u^5-0.10079u^6+0.012369u^7-0.00094357u^8+4.0678\times10^{-5}u^9-7.5694\times10^{-7}u^{10}$	For 0<u<3.5
ISENDCO_SP	$1.86144723+0.021989(u-3.5)$	For u≥3.5
ISENDCO_L	$0.60896+3.0593u-3.9339u^2+2.933u^3-1.3353u^4+0.38696u^5-0.072771u^6+0.0088395u^7-0.00066864u^8+2.8623\times10^{-5}u^9-5.2941\times10^{-7}u^{10}$	For 0<u<4.5
ISENDCO_L	$1.9283751+0.016846129(u-4.5)$	For u≥4.5

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