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CONTROL OF TIME-DELAY PROCESSES USING CONTROLLER DESIGNED BASED ON POLE PLACEMENT METHOD

Saša Lj. Prodanović[1], Ljubiša M. Dubonjić[2]
[1]University of East Sarajevo, Faculty of Mechanical Engineerng, East Sarajevo, Bosnia and Herzegovina
[2] University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo, Kraljevo, Serbia
e-mail: sasa.prodanovic77@gmail.com, sasa.prodanovic@ues.rs.ba, dubonjic.lj@mfkv.kg.ac.rs

Abstract: Due to many problems in the system control caused by time delay present paper, like many others, deals with such a kind of processes. Approximation and reduction of mathematical model of process have been carried out, in order to adapt it for controller design according pole placement method. Proposed procedure was researched and proven on the two different processes. First, single-input single-output (SISO) process and the other multivariable process with two-inputs and two-outputs (TITO), both with time delay. Investigation has been carried out using simulations.
Key words: time-delay processes, model approximation, PI controller, pole placement method

INTRODUCTION

Processes with time delay are very common in the many areas of life. Due to that, interest in their control is very frequent. Regardless whether time delay is caused by process nature or delay of measurement signal, it makes troubles in process control. A lot of researches and publications are referred to time-delay systems and its control, like in [1-4]. Various methods for analysis and design of controller for this kind of processes were presented herein. Pole placement method is very useful approach for controller design, because few parameters is used in defining of controller's terms (proportional, integral and/or derivative) and therefore system dynamical behavior. There is a lot of literature for this method, too. Some of them are presented in [5-8]. Taking into account general expressions of the pole placement method, it is evidently, that mathematical models of many processes have to be adjusted for applying of this method. Many types of approximations are available from literature but Padé approximation, presented in [9], has been used in this investigation. Therefore, procedure of PI controller design, using pole placement method, for time-delay processes control has been suggested here. The paper is organized in the following way. Short literature overview of thematic area and paper content are given in this chapter. Chapter *Controller design* contain explanation of pole placement method and preconditions for its application. Representative processes (SISO and TITO) are simulated in the chapter *Examples*. Chapter *Conclusions* gives some notes and guidelines about presented procedure. *References* are listed in the last chapter.

CONTROLLER DESIGN

Pole placement method

Among numerous literature sources that deal with pole placement method for PI controller design, this investigation is based on [10]. Initially for PID controller design, process transfer function $G(s)$ has to be in the form (1):

$$G(s)=\frac{K}{(T_1 s+1)(T_2 s+1)} \tag{1}$$

where are K – process gain, T_1 and T_2 – time constants.

Controller's $G_c(s)$ general form is presented by (2). The meaning of the parameters is: K_p, K_i and K_d – proportional, integral and derivative gain, respectively, T_i and T_d – integral and derivative time constant.

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) = K_p + \frac{K_i}{s} + K_d s \tag{2}$$

Taking into account well known transfer function of the closed loop and roots of the characteristic equation (poles of the system), desired system behavior is described by the following equation (3):

$$(s + \alpha\omega_n)\left(s^2 + 2\xi\omega_n s + \omega_n^2\right) = 0 \tag{3}$$

where are ω_n – natural frequency of the process, ξ – damping degree, $-\alpha\omega_n$ – real pole whose real part should be several times larger than two dominant poles. Parameter α serve for controller adjusting.
According [10] expressions for PID controller's parameters are:

$$\begin{aligned} K_p &= \frac{T_1T_2\omega_n^2(1+2\xi\alpha)-1}{K} \\ T_i &= \frac{T_1T_2\omega_n^2(1+2\xi\alpha)-1}{T_1T_2\alpha\omega_n^3} \\ T_d &= \frac{T_1T_2\omega_n(\alpha+2\xi)-T_1-T_2}{\omega_n^2T_1T_2(1+2\xi\alpha)-1} \end{aligned} \tag{4}$$

Model approximation and reduction

As it can be seen in previous subchapter, procedure for PID controller design according pole placement method is pretty simple. The problem is that many processes cannot be described in form (1), which means that they have zeros and/or they are not of the second order. In order to apply above presented pole placement method process transfer function should be approximated and even reduced its order. In doing so, care must be taken to ensure that deviations in system responses are acceptable, i.e. it mustn't disturb controller design. Transfer function of the time-delay system $G(s)$ is product of rational and exponential term (5). Obviously, exponential term, that represents time delay, should be approximated. Padé approximation of degree 1 is used here (6), in order to avoid order rising of entire system.

$$G(s) = \frac{K}{Ts+1}e^{-Ls} \tag{5}$$

$$e^{-Ls} = \frac{2-(Ls)}{2+(Ls)} \tag{6}$$

where is L – time delay.
If process transfer function is second or higher order, after approximation we get transfer function of the entire system which is third order or higher. In that case model reduction must be carried out. It can be done in the software Matlab.

EXAMPLES

Two different time-delay processes were simulated in order to prove possibilities for applying proposed procedure. One single-input single-output (SISO) process and the other multivariable twoinput two-output (TITO) were deliberately tested, with a view to show diversity and effectiveness of procedure in the case when mutual coupling is present.

First example

In this example direct heat exchanger was taken into consideration. Voltage drop $U(t)$ is manipulated variable, while liquid temperature $\vartheta(t)$ is controlled variable (response) of the system. It was modeled as time-delay process in [11] and its transfer function is shown by (7).

$$G(s)=\frac{2,38}{50,264s+1}e^{-10s} \tag{7}$$

After Padé approximation (6) and algebraic transformations transfer function becomes (8).

$$G(s)=\frac{-11,75s+2,25}{(5s+1)(50s+1)} \tag{8}$$

Model reduction (9) was allowed, because neglection of right half plane zero didn't significantly distorted compared step responses of the process, as it can be seen in Fig. 1. Now, process transfer function is:

$$G(s)=\frac{2,25}{(5s+1)(50s+1)} \tag{9}$$

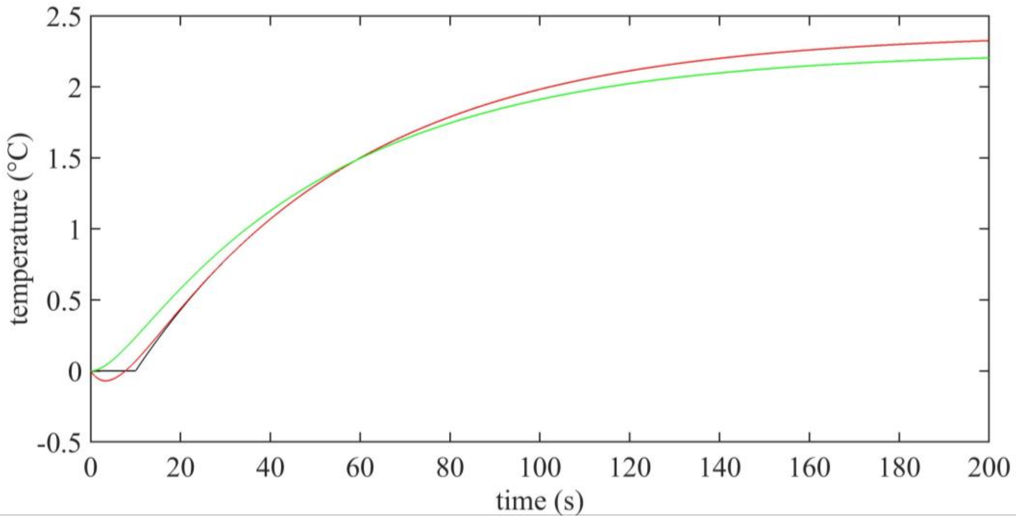

Figure 1. Comparative display of three stage of process transfer function presented by equations: ____ (7), ____ (8) and ____ (9)

According equations (1) and (9) following parameters are obtained: K=2,25 ; T_1=5 s ; T_2=50 s ; ω_n=0,02 rad/s ; ξ=1. Parametar α has been chosen as α=12 to place non-dominant pole far enough from the origin. Parameters of PID controller $G_c(s)$ calculated from (4) are: K_p=0,667 ; K_i=0,011; K_d=6,667. They were applied in configuration shown in Fig 2, where: r – reference value (It was set as r=20 °C), u – manipulative value and y – proces response (output).

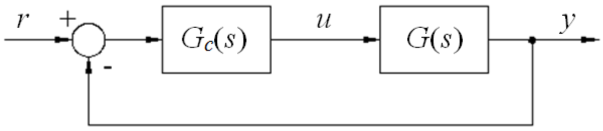

Figure 2. Configuration for testing (SISO) process

After perform simulations in Matlab software, it was noticeable that derivative term causes needless dynamic in the process response. Therefore, derivative term was dismissed, and PI controller has been used for process control. It enables pretty good response (shown in Fig. 3), because there is no overshoot while response speed is acceptable.

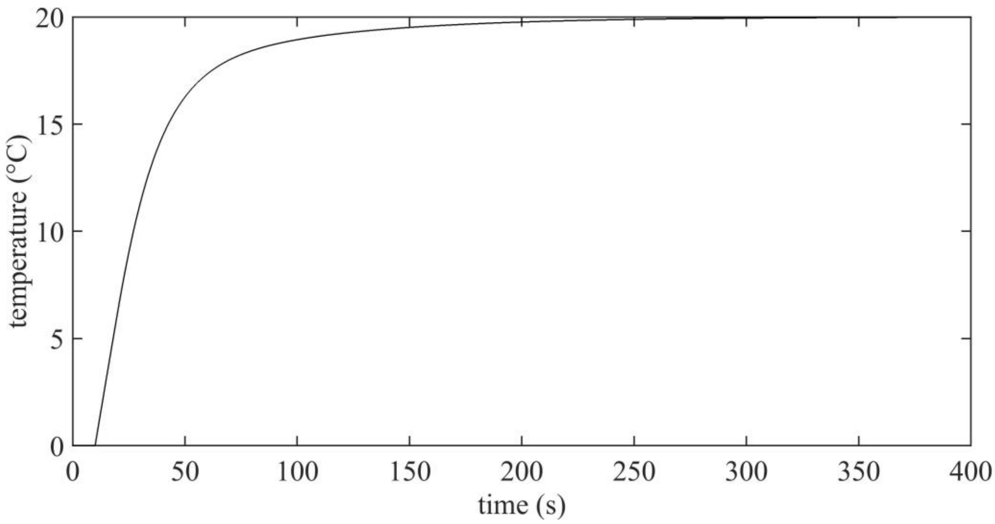

Figure 3. Response of the direct heat exchanger

Second example

Binary distillation column (water-methanol) has been frequently used as object for testing various control algorithms. Its mathematical model (10) was formed in [12]. Controlled variables are: $X_D(s)$ – percentage of methanol in the distillate, $X_B(s)$ – percentage of methanol in the bottom products, and manipulated variables are: $R(s)$ – reflux flow rate and $S(s)$ – steam flow rate in the reboiler.

$$\begin{bmatrix} X_D(s) \\ X_B(s) \end{bmatrix} = G(s) \times \begin{bmatrix} R(s) \\ S(s) \end{bmatrix}$$

$$G(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} = \begin{bmatrix} \frac{12,8}{16,7s+1}e^{-s} & \frac{-18,9}{21s+1}e^{-3s} \\ \frac{6,6}{10,9s+1}e^{-7s} & \frac{-19,4}{14,4s+1}e^{-3s} \end{bmatrix} \tag{10}$$

In order to compensate influence of mutual coupling and in that way, enable proper controller design, this multivariable process has been decoupled using simplified decoupling procedure (11) and (12). It was done in [13]. Where $d_{12}(s)$ and $d_{21}(s)$ are terms of decoupler $D(s)$.

$$D(s)=\begin{bmatrix}1 & d_{12}(s)\\ d_{21}(s) & 1\end{bmatrix}=\begin{bmatrix}1 & \dfrac{-g_{12}(s)}{g_{11}(s)}\\ \dfrac{-g_{21}(s)}{g_{22}(s)} & 1\end{bmatrix} \qquad (11)$$

$$d_{12}(s)=1{,}47\frac{16{,}7s+1}{21s+1}e^{-2s}, \qquad d_{21}(s)=0{,}34\frac{14{,}4s+1}{10{,}9s+1}e^{-4s} \qquad (12)$$

After decoupling, following diagonal transfer matrix of the process was obtained. It is presented by (13) and (14) [13]:

$$Q=\begin{bmatrix}g_{11} & g_{12}\\ g_{21} & g_{22}\end{bmatrix}\cdot\begin{bmatrix}d_{11} & d_{12}\\ d_{21} & d_{22}\end{bmatrix}=\begin{bmatrix}g_{11}d_{11}+g_{12}d_{21} & g_{11}d_{12}+g_{12}d_{22}\\ g_{21}d_{11}+g_{22}d_{21} & g_{21}d_{12}+g_{22}d_{22}\end{bmatrix}=\begin{bmatrix}q_1 & 0\\ 0 & q_2\end{bmatrix} \qquad (13)$$

In the (13) Laplace operator *s* was omitted because of shorter writing.

$$Q(s)=\begin{bmatrix}\dfrac{12{,}8\cdot e^{-s}}{16{,}7s+1}-\dfrac{6{,}4(14{,}4s+1)\cdot e^{-7s}}{228{,}9s^2+31{,}9s+1} & 0\\ 0 & -\dfrac{19{,}4\cdot e^{-3s}}{14{,}4s+1}+\dfrac{9{,}7(16{,}7s+1)\cdot e^{-9s}}{228{,}9s^2+31{,}9s+1}\end{bmatrix} \qquad (14)$$

Having in mind (10), (13), (14) and (1) it is obvious that terms q_1 and q_2 are not in appropriate form for controller design according pole placement method. So, both of them were subjected to Padé approximation and reduction of model order using Matlab software. Hence:

$$q_1(s)=\frac{-0{,}5644s^2+0{,}9406s+0.1892}{s^2+0{,}4785s+0{,}02957} \qquad (15)$$

$$q_2(s)=\frac{-0{,}4384s^2+2{,}647s-2{,}909}{s^2+2{,}975s+0{,}2999} \qquad (16)$$

Neglecting of one right half plane zero and one left half plane zero in q_1, and two right half plane zero in q_2 leads to following forms (17) and (18).

$$q_1(s)=\frac{6.307}{(2{,}463s+1)(13{,}699s+1)} \qquad (17)$$

$$q_2(s)=\frac{-9{,}729}{(0{,}348s+1)(9.615s+1)} \qquad (18)$$

This reductions (17) and (18) are allowed because deletion of mentioned zeros didn't significantly distorted process step responses, as it can be seen in Fig. 4 and 5.

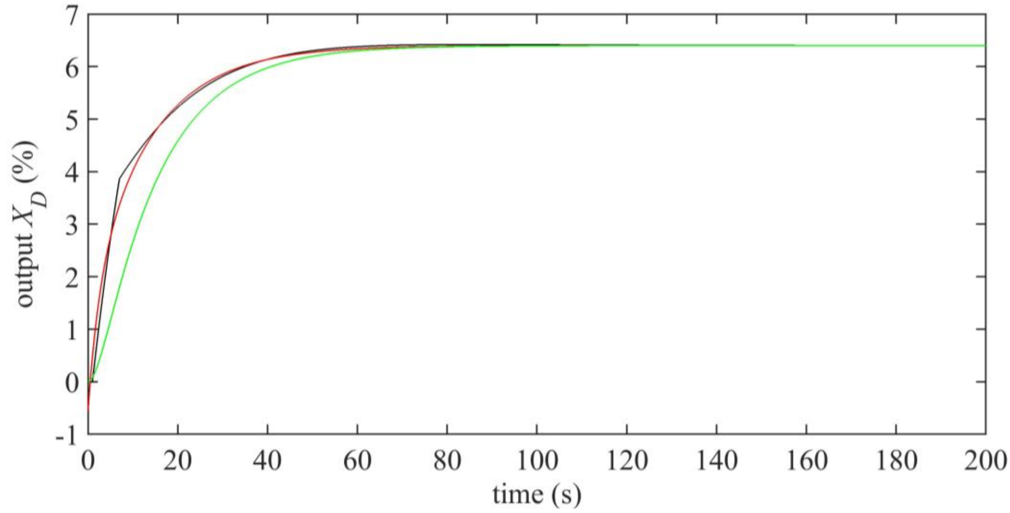

Figure 4. Comparative display of three stage of process transfer function presented by equations: ____ q_1(14), ____ (15) and ____ (17)

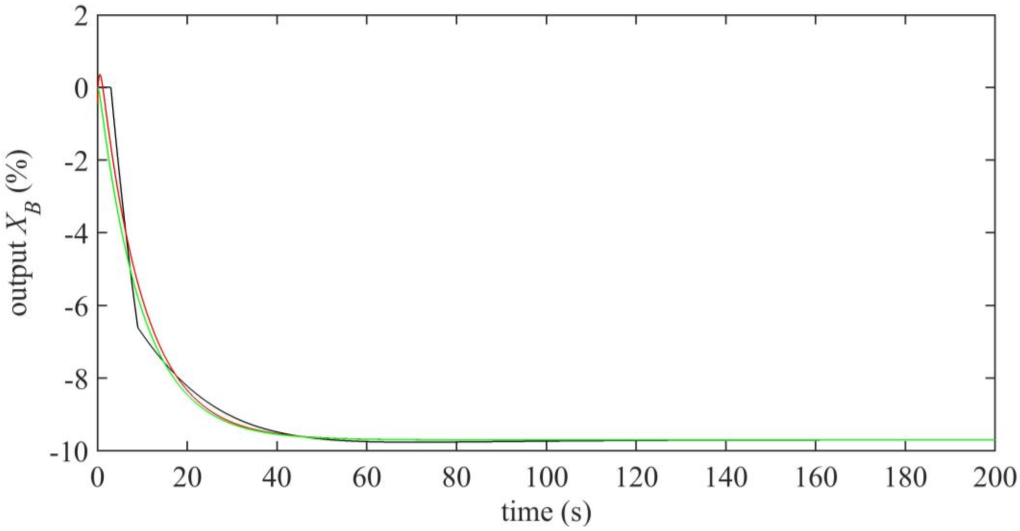

Figure 5. Comparative display of three stage of process transfer function presented by equations: ____ q_2(14), ____ (16) and ____ (18)

Equations (1) and (17) give following parameters (for the first loop): K=6,307 ; T_1=2,463 s ; T_2=13,699 s ; ω_n=0,073 rad/s ; ξ=1. Parametar α has been chosen as α=6 to place non-dominant pole far enough from the origin. Parameters of PID controller G_{c1} calculated from (4) are: K_p=0,2121 ; K_i=0,0125; K_d=0,5617.

On the same way, equations (1) and (18) give following parameters (for the second loop): K=-9,729 ; T_1=0,348 s ; T_2=9,615 s ; ω_n=0,104 rad/s ; ξ=1. Parametar α has been chosen as α=18 to place non-dominant pole far enough from the origin. Parameters of PID controller G_{c2} calculated from (4) are: K_p=-0,0348 ; K_i=-0,007; K_d=0,3087.

All of these parameters were applied in configuration shown in Fig. 6, where: r_1 and r_2 – reference values (set as 1), e_1 and e_2 – errors of controlled variables, v_1 and v_2 – outputs of controllers, u_1 and u_2 – manipulative values and y_1 and y_2 – process responses (outputs).

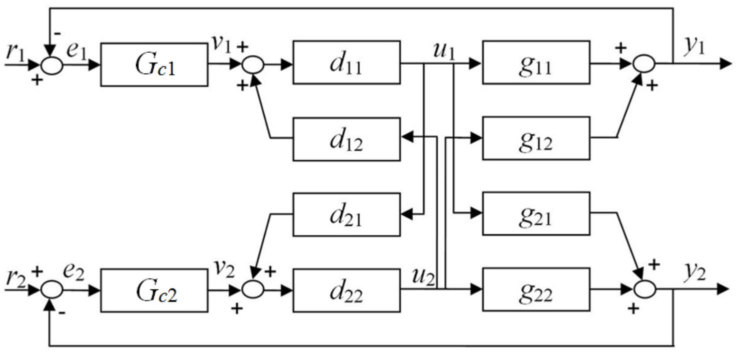

Figure 6. Configuration for testing multivariable process

In the Fig. 6 Laplace operator s was omitted to make it simpler.
Simulations carried out in Matlab software give process responses shown in Fig.7. Derivative term in this process introduce needless dynamic in the process response. Due to that, it was dismissed and therefore PI controller has been used for process control. Fig. 7 shows that PI controller gives first output without overshoot and the second one with a little bit of overshoot. Speed of both responses is good enough.

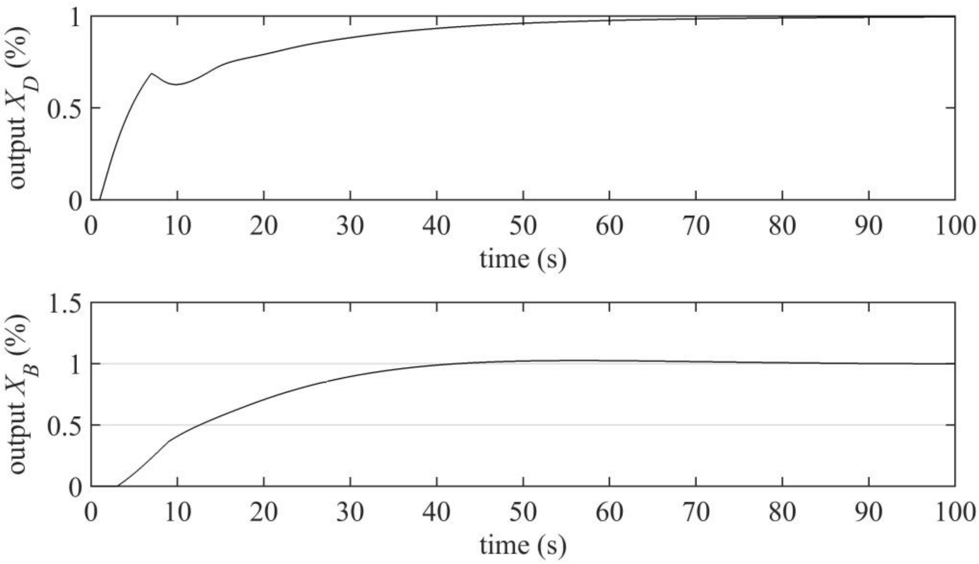

Figure 7. Responses of the binary distillation column (water-methanol)

CONCLUSION

One more procedure for controller design and activities preceding it is presented here. It is proved and emphasized that proper approximation and reduction of model, if they are necessary, contribute to successful controller design. In the case of multivariable systems, there are more phases of approximation and reduction. Pole placement method in the combination with above mentioned steps gives controller that enables pretty good process responses. Depending on the particular process, parameter α, that define non-dominant pole, can be placed on the various distance from the origin in order to obtain good behavior of the entire control system. Despite the defined calculation, if any of the controller parameters impair the response quality (often derivative term), it should not be used like in presented examples where PI controllers were utilized.

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