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SIMPLE TUNING OF PID CONTROLLERS USED WITH OVER DAMPED SECOND-ORDER PROCESSES

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ABSTRACT

PID controllers are used for decades in controlling processes in linear feedback control systems. Their use requires accurate and effective tuning to satisfy an acceptable performance for the control system.

Large number of processes are classified as or approximated by a second order model. They may me under damped, critically damped or over damped. This paper presents the tuning of PID-controllers used with second order over damped processes. The process damping ratio is from 1 to 10 and its natural frequency is from 2.5 to 15 rad/s. The tuning technique depends or minimizing the integral of square of error (ISE) between the time response of the system to a unit step input and its steady-state response. It was possible to achieve a PID-controlled system with controllable overshoot and settling time. The tuning results are listed in tables for direct use depending on process damping ratio and natural frequency.

The tuning approach is reduced to only one set of controller parameters to simplify the tuning process used with any process approximated by a second-order over damped model. The tuning results are compared with controller tuning using standard forms showing better performance of the control system using the proposed tuning in the present work regarding the maximum percentage overshoot and settling time of the control system using both exact and simple tuning parameters of the PID-controller.

KEYWORDS: Over Damped Second Order Processes, PID Controllers, Simple Controller Tuning, MATLAB Optimization Application

INTRODUCTION

PID-controllers have simple construction using operational and new generation amplifiers [1,2,3]. PID-controllers still find interest of control engineering researchers. Sung and Lee (2000) proposed an identification algorithm for the automatic tuning of PID controllers to guarantee better accuracy and to provide more frequency data sets of the process [4]. Vrancic, Strmcnik and Turicic (2001) used the multiple integration of the process time response for calculating the parameters of the PID controller [5]. Shen (2002) proposed a tuning method for PID controller providing the performance assessment formulas. His method is based on a genetic algorithm-based design technique [6]. Tavakoli and Tavakoli (2003) presented a tuning technique for PID controllers controlling first-order plus delay processes based on dimensional analysis and optimization techniques. They used ISE, IAE and ITAE performance criteria [7]. Gaing (2004) presented a design method for determining the optimal PID controller parameters of an AVR system using the particle swarm optimization algorithm providing high-quality solution [8].

Syrcos and Kookes (2005) presented a general mathematical formulation for the development of customized PID control tuning. The presented a number of case studies clarifying their proposed methodology [9]. Chen and Chang (2006) studied the optimal design of a PID controller for an active magnetic bearing using genetic algorithms providing experimental and simulation results [10]. D'Emilia, Marra and Natale (2007) described a theoretical-experimental approach allowing the evaluation of the adequateness of new methods for auto-tuning with respect to traditional ones [11]. Ramasamy and Sundaramoorthy (2008) used the impulse response instead of the step response of the plant to tune the PID controller, requiring no approximation of the plant by any model.

They derived formulae for the calculation of PID controller tuning parameters [12]. Malwatker, Sonawane and Waghmane (2009) proposed a model-based design of PID controllers for higher-order oscillating systems. They obtained the controller parameters from a reduced third-order model and presented examples to demonstrate the effectiveness of their proposed method [13].

Pai, Chang and Huang (2010) presented a simple calculation method of a PI/PID controller tuning for integrating processes with dead-time and inverse response based on a model [14]. Matausek and Sekara (2011) proposed a tuning procedure for ideal PID controller in series with a first-order noise filter based on the extension of Ziegler-Nichols frequency domain dynamics of a process [15]. Ayala and Foelh (2012) presented the design and tuning of two PID controllers using the non-dimensional sorting genetic algorithm approach offering simple and robust solutions providing good reference tracking performance [16]. Saglam, Tutomo and Kurtulan (2013) presented a PI controller tuning method for cooling of the hydrogen production unit within the polymer electrolyte membrane fuel cell based micro-cogeneration system. Their proposed analytical tuning rules are based totally on the model parameters using the digital control theory and experiences in industrial control problems [17]. Venugopal, Ganguly and Singh (2013) used soft computing methodology based on fuzzy logic to design and tune PID controllers for better performance [18]. Arturo et. al. (2013) developed a methodology for PID controller tuning by coupling the gain-phase margin method with the genetic algorithms.

They applied the proposed technique using MATLAB simulation and experimentally on CNC machines and an industrial robot [19]. Baloochy (2013) employed a self-regulating approach using the relay oscillation method to specify process parameters. He used the modified Zeigler-Nichols tuning method to tune the PID family of controllers [20]. Korsane, Yadav and Raut (2014) demonstrated using a method of tuning PID controllers using different tuning techniques. They implied their technique to a PID controller used with a first-order plus time delay [21]. Srinivas, Lakshmi and Kumar (2014) compared the performance of genetic algorithms based PID controller with conventional PID controller for various tuning techniques in the case of three tank level process for set-point tracking [22]. Aborisade and Adewuyi (2014) studied the temperature control of a gas-fired oven using a PID controller. They implemented the Ziegler- Nichols, good gain and Skogestad's tuning methods to control the output temperature of the oven [23].

ANALYSIS

Process

The process has the transfer function:

$$M_p(s) = \omega_n^2 / (s^2 + 2\zeta\omega_n s + \omega_n^2) \qquad (1)$$

The second-order process of Eq.1 may be for an exact second-order process or of a non- oscillating dynamic system of order higher than 2 and can be approximated by a second-order one. The damping ratio of the second order system is in the range: $1 \leq \zeta \leq 10$

Controller

The controller used in this study is a proportional + integral - derivative (PID)- controller.

The PID-controller has a transfer function $G_c(s)$ given by:

$$G_c(s) = K_{pc} + (K_i/s) + K_d s \quad (2)$$

Where: K_{pc} = controller proportional gain

K_i = controller integral

K_d = controller derivative gain

Control System Transfer Function

Assuming that the control system is a unit feedback one, its transfer function becomes:

$$M(s) = (b_0 s^2 + b_1 s + b_2) / (s^3 + a_1 s^2 + a_2 s + a_3) \quad (3)$$

where

$b_0 = \omega_n^2 K_d$, $b_1 = \omega_n^2 K_{pc}$

$b_2 = \omega_n^2 K_i$, $a_1 = 2\zeta\omega_n + \omega_n^2 K_d$

$a_2 = \omega_n^2(1 + K_{pc})$, $a_3 = \omega_n^2 K_i$

System Step Response

A unit step response is generated by MATLAB using the numerator and deniminator of Eq. 3 providing the system response c(t) as function of time [24].

Controller Tuning

The sum of absolute error (ISE) is used as an objective function, F required by the optimization process. Thus:

$$F = \int [c(t) - c_{ss}]^2 \quad (4)$$

where c_{ss} = steady-state response of the system ($c_{ss} = b_2/a_3$).

The performance of the control system is judged using two functional parameters:

The maximum percentage overshoot, OS_{max}

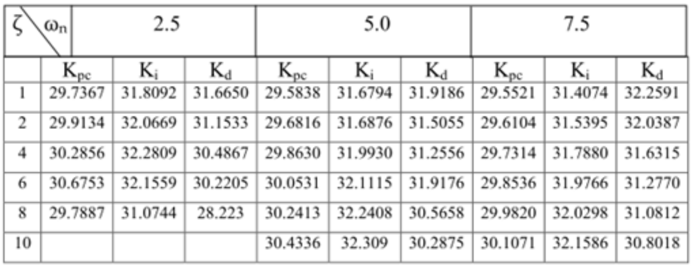
The settling time, T_s

The maximum percentage overshoot and the settling time of the control system are obtained using the *stepinfo* command of MATLAB [24]. The optimization procedure used depends on the MATLAB optimization toolbox using the command "*fminunc*". Thus, it does not need the definition of any functional constraints. In this case the judgement of the tuning results depends on the values of the step response maximum overshoot and settling time.

Tuning Results

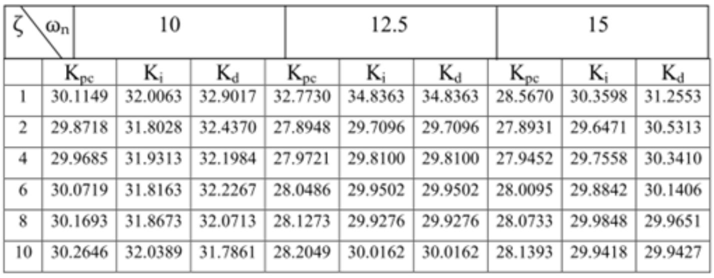
A MATLAB code is written with process parameters ω_n and ζ as input parameters and the parameters of the controller are evaluated by minimizing the objective function (Eq.4) using the command "*fminunc*". Tables 1 and 2 presents the results of the optimal tuning procedure used in this work for process natural frequencies in the range: $2.5 \le \omega_n \le 15$ rad/s

Table 1: PID-Controller Tuning for over Damped Second-Order Processes Having a 2.5, 5, 7.5, rad/s Natural Frequencies



ζ \ ω_n	2.5			5.0			7.5		
	K_{pc}	K_i	K_d	K_{pc}	K_i	K_d	K_{pc}	K_i	K_d
1	29.7367	31.8092	31.6650	29.5838	31.6794	31.9186	29.5521	31.4074	32.2591
2	29.9134	32.0669	31.1533	29.6816	31.6876	31.5055	29.6104	31.5395	32.0387
4	30.2856	32.2809	30.4867	29.8630	31.9930	31.2556	29.7314	31.7880	31.6315
6	30.6753	32.1559	30.2205	30.0531	32.1115	31.9176	29.8536	31.9766	31.2770
8	29.7887	31.0744	28.223	30.2413	32.2408	30.5658	29.9820	32.0298	31.0812
10				30.4336	32.309	30.2875	30.1071	32.1586	30.8018

Table 2: PID-Controller Tuning for over Damped Second-Order Processes Having a 10,12.5, 15, rad/s Natural Frequencies



ζ \ ω_n	10			12.5			15		
	K_{pc}	K_i	K_d	K_{pc}	K_i	K_d	K_{pc}	K_i	K_d
1	30.1149	32.0063	32.9017	32.7730	34.8363	34.8363	28.5670	30.3598	31.2553
2	29.8718	31.8028	32.4370	27.8948	29.7096	29.7096	27.8931	29.6471	30.5313
4	29.9685	31.9313	32.1984	27.9721	29.8100	29.8100	27.9452	29.7558	30.3410
6	30.0719	31.8163	32.2267	28.0486	29.9502	29.9502	28.0095	29.8842	30.1406
8	30.1693	31.8673	32.0713	28.1273	29.9276	29.9276	28.0733	29.9848	29.9651
10	30.2646	32.0389	31.7861	28.2049	30.0162	30.0162	28.1393	29.9418	29.9427

SIMPLIFYING THE TUNING PARAMETERS

Having a detailed insight to the controller parameters values in Tables 1 and 2 we find that they are close to each other except for the derivative parameter at some of the process natural frequencies. This has given an idea of taking the average of all the controller parameters values. This step results in an average proportional, integral and derivative gain of:

$$\left.\begin{aligned} &K_{pcav} = 29.5776 \quad \text{with standard deviation of 1.3733.} \\ &K_{iav} = 31.4980 \quad \text{with standard deviation of 1.3948.} \\ &K_{dav} = 31.2383 \quad \text{with standard deviation of 1.5576.} \end{aligned}\right\} \qquad (5)$$

COMPARISON WITH STANDARD FORMS TUNING

To examine the effectiveness of the simplified tuning procedure used in this work, it has been compared with the results of controller tuning using the ITAE-based standard forms [25]. The standard characteristic equation of a second-order closed-loop control system of the form given in Eq.3 is [25]:

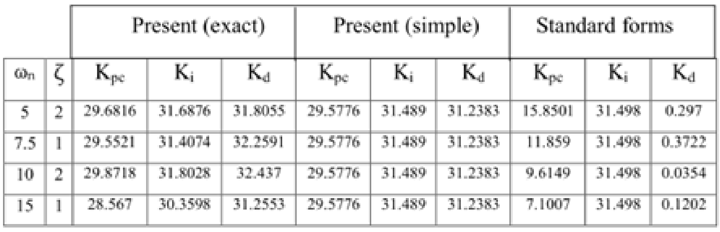
$$s^3 + 2.97\omega_o s^2 + 4.94\omega_o^2 s + \omega_o^3 = 0 \qquad (6)$$

The PID-controller parameters are tuned using the standard forms for a specific process natural frequency and damping ration by comparing the coefficients of the characteristic equations in Eqs.3 and 6, giving:

$$\left.\begin{aligned} \omega_o &= (\omega_n^2 K_i)^{1/3} \\ K_{pc} &= (4.94\omega_o^2 / \omega_n^2) - 1 \\ K_d &= (2.97\omega_o - 2\zeta\omega_n) / \omega_n^2 \end{aligned}\right\} \quad (7)$$

Using Tables 1 and 2 and Eqs.5 and 7, the tuned controller parametrs of the PID controller using the exact tuning, simplified tuning and the standard forms for a selected values of process natural frequency and damping ratio are given in Table 3.

Table 3: PID-Controller Tuning for over Damped Second-Order Processes



		Present (exact)			Present (simple)			Standard forms		
ω_n	ζ	K_{pc}	K_i	K_d	K_{pc}	K_i	K_d	K_{pc}	K_i	K_d
5	2	29.6816	31.6876	31.8055	29.5776	31.489	31.2383	15.8501	31.498	0.297
7.5	1	29.5521	31.4074	32.2591	29.5776	31.489	31.2383	11.859	31.498	0.3722
10	2	29.8718	31.8028	32.437	29.5776	31.489	31.2383	9.6149	31.498	0.0354
15	1	28.567	30.3598	31.2553	29.5776	31.489	31.2383	7.1007	31.498	0.1202

The time response of the control system using the three sets of PID-controller parameters of Table 3 is compared in Figures 1 - 5:

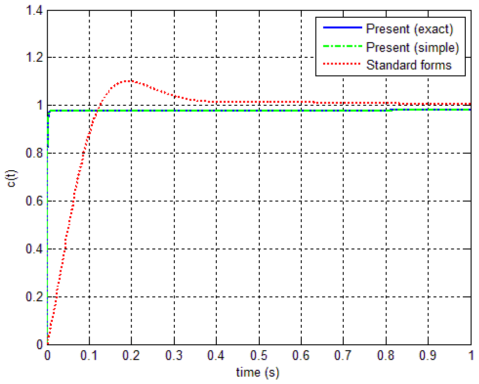


Figure 1: Unit Step Response of the PID Controlled Second-Order Process Having ω_n = 5 and ζ = 2

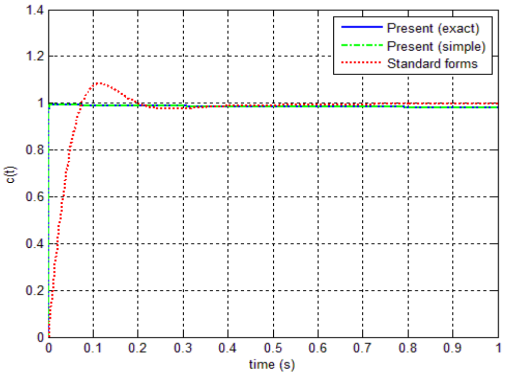


Figure 2: Unit Step Response of the PID Controlled Second-Order Process Having ω_n = 7.5 and ζ = 1

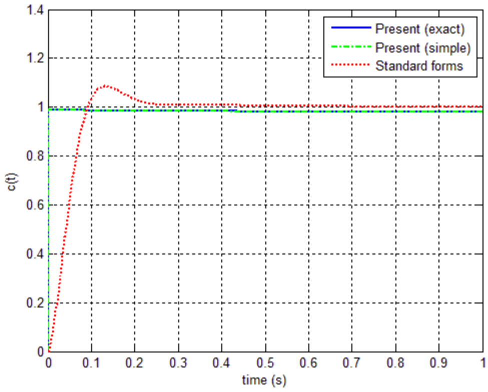


Figure 3: Unit Step Response of the PID Controlled Second-Order Process Having $\omega_n = 10$ and $\zeta = 2$

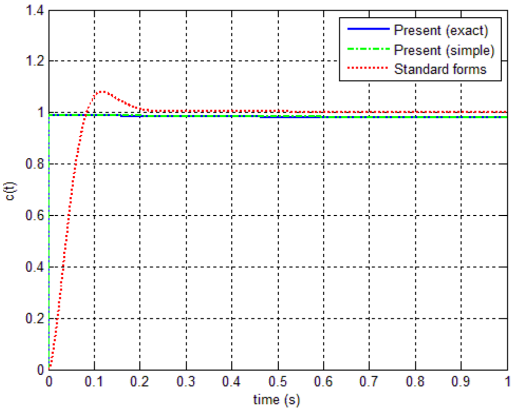


Figure 4: Unit Step Response of the PID Controlled Second-Order Process Having $\omega_n = 12.5$ and $\zeta = 2$

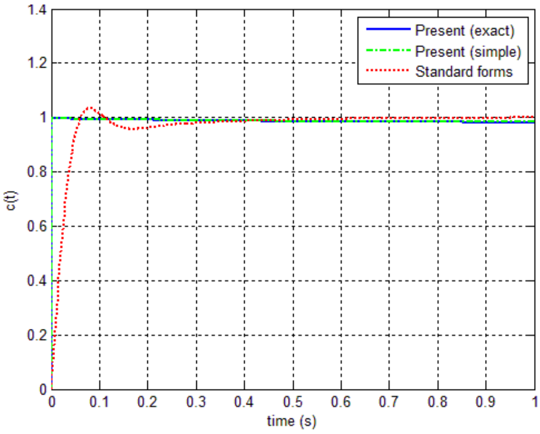
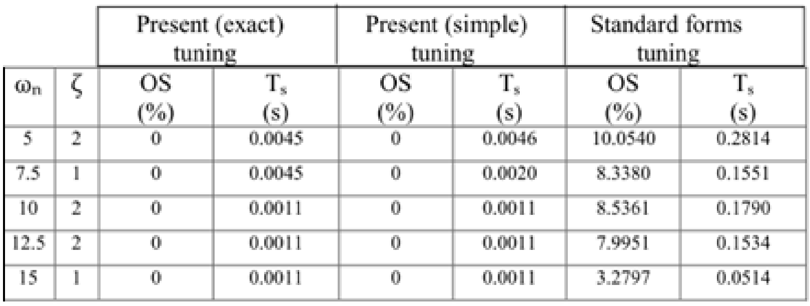


Figure 5: Unit Step Response of the PID Controlled Second-Order Process Having $\Omega_n = 15$ and $Z = 1$

The peformance of the PID-controlled overdamped second-order process in terms of the control system maximum percentage overshoot and settling time is compared in Table 4. The maximum percentage undershoot is zero for all the controller parameters sets.

Table 4: Comprasion of the Control System Performance



		Present (exact) tuning		Present (simple) tuning		Standard forms tuning	
ω_n	ζ	OS (%)	T_s (s)	OS (%)	T_s (s)	OS (%)	T_s (s)
5	2	0	0.0045	0	0.0046	10.0540	0.2814
7.5	1	0	0.0045	0	0.0020	8.3380	0.1551
10	2	0	0.0011	0	0.0011	8.5361	0.1790
12.5	2	0	0.0011	0	0.0011	7.9951	0.1534
15	1	0	0.0011	0	0.0011	3.2797	0.0514

CONCLUSIONS

- It is possible to suppress higher oscillations and very large settling time associated with higher-order dynamic processes through using PID-controllers.
- Through using a PID-controller it was possible to control the time-based specifications of the closed-loop control system through tuning the controller.
- The integral of the error square criterion (ISE) was used to tune the PID-controller.
- The tuning procedure was reduced to the assignement of a one set of controller parameters independent of the process damping ratio and natural frequency.
- The performance of the control system was compared for 3-sets of tuning paprameters: the exact parmameters obtained in the present work, the simple tuning one set, and the tuning parameters obtained using the standard forms.
- The maximum percentage ovedrshoot and the settling time using the present tuning parameters were superior with respect to those obtained using the standard forms tuning technique.
- The simple tuning set of the PID-controller parameters has given the same performance parameters as the exact sets of parameters.
- Using the simple set is sufficient in tuning PID-controllers used with processes approximated by an overdamped second-order model.
- Maximum percentage overshoot was as low as 0.0045 % compared with about 10 % using the tuning approach of standard forms.

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