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Tuning of a Novel P-D Compensator to Control a Highly Oscillating Second-order-like Process

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ABSTRACT

This paper presents a novel P-D compensator to control a highly oscillating second order process. The compensator parameters are tuned using a simple way based on the MATLAB optimization toolbox and then compared with compensator parameters using another tuning technique and the characteristics of the control system are compared. The proposed compensator was compared with four other compensators used to control the same process, one from the first compensator generation and three from the second compensators generation. Control system characteristics are compared graphically through the step time response to reference input and numerically through tabulation.

Keywords: *P-D compensator, second compensator generation, compensator tuning, control system characteristics*

INTRODUCTION

The author presented in 2014 and 2015 a series of research papers aiming at introducing a new generation of control compensators to replace the old ones used during the 20th century. He called those in the 20th century the *'first generation of compensators'* and those who presented in 2014 and 2015 the *'second generation of compensators'*. Here is the objectives of the new compensators he presented in the *'second compensator generation'*.

In February 2014 he presented a paper about the tuning of a feedback PD compensator used to control underdamped second order processes having damping ratio from 0.05 to 0.8. He could achieve time response for step input tracking with maximum percentage overshoot of 0.1 % [1]. In April 2014 he published a paper about tuning a novel feedback first order compensator for the control of a highly oscillating second order process as an example of processes having bad dynamic characteristics. This process had 85.6 % maximum percentage overshoot which is a real challenge for the control engineer to select a controller or a compensator to go down with this high value to a reasonable level. Through compensator tuning he could go down with the maximum overshoot to only 0.099 % and the settling time to only 0.388 s instead of ..... for the process without control [2]. In July 2014 he published another paper aiming at the application of feedback PD compensator to control a third order process of 85.4 % maximum percentage overshoot. He succeeded to tune the compensator to reduce the characteristics of the closed loop control system to about 5 % overshoot, 6.2 s settling time and 0.02 steady state error [3]. .

In July 2014 he published a paper for the tuning of a novel feedforward 2/2 second order compensator to control a very slow second-order-like process having 11.2 damping ratio. Through tuning he could produce time response for step reference input tracking with zero maximum overshoot, 0.22 s settling time and 0.01 steady state error [4]. In July 2014 the author presented a novel notch compensator to control the highly oscillating second order process. He could reduce the maximum percentage overshoot of the closed loop control system incorporating the compensator and the process to only 0.55 %, the settling time to only 0.03 s and the steady state error to 0.0066 [5]. In November 2014 the author presented a novel Sallen-Key compensator to control the highly oscillating process. Through compensator tuning he could generate time response for step input tracking without any overshoot , but with settling time of about 70 s [6]. In September 2014 the author studied the robustness of notch and Sallen-Key compensators when used to control a highly oscillating second order process. The study showed that the Sallen-Key compensator is robust for the whole range of ± 20 % change in the process parameters. The notch compensator was not robust when the change in process parameters was negative [7].

In the beginning of 2015 he presented a work for the disturbance rejection associated with delayed double integrating processes with time delay between 0.1 and 0.9 s using a tuned feedback PD compensator. Depending on the time delay the maximum response was between zero and 6 and the steady state error from 0 to 0.9 [8]. In January 2019 he investigated the robustness of feedback first order lag-lead , feedforward second order lag-lead and feedforward first order lag-lead compensators used to control second order processes. He concluded that the studied controllers are robust when used with both highly oscillating and very slow second order processes [9]. In May 2015, the author presented a novel third order feedforward compensator to control a highly oscillating second order processes with 85.4 and 52.6 % maximum percentage overshoots for reference input tracking. Through compensator tuning he could reduce the maximum overshoots to 0.35 % for the first process and 0 for the second process and the settling time to 2.1 and 1.76 s respectively [10]. Also, in May 2015 he presented a novel feedforward third order compensator used to control a delayed integrating process with delay time from 0.2 to 3 s. He could, through compensator tuning, to eliminate completely the maximum percentage overshoot (zero overshoot) for time delay ≤ 0.6 s with settling time around 8 s [11]. In June 2015 the author presented a feedback lag-lead first order compensator to control a fractional time delay do0uble integrating process with time delay from 0.1 to 0.8 s. He could, through compensator tuning, achieve time response to step reference input tracking with 0.21 % maximum overshoot and 3.5 s settling time for 0.4 s time delay [12].

In July 2015 the author tuned a novel second order compensator to control the highly oscillating second order process. He could, through compensator tuning, obtain a step time response for reference input tracking without any overshoot, with 8.57 s settling time and 0.01 steady state error [13]. In September 2015 he studied the tuning of a feedback lag-lead first order compensator for the disturbance rejection associated with delayed double integrating processes . The maximum percentage overshoot attained with such processes depended on the time delay of the process [14]. In December 2021 the author published a paper in which he tuned a 2/2 second order control compensator from the first compensator generator and compared the performance of the control system for step reference tracking with five compensators from the second compensator generation when all of them used to control the highly oscillating second order process. The controller from the first generation could not compete with the five compensators from the second generation regarding the maximum percentage overshoot of the closed loop control system. It could compete with four compensators from the second generator regarding the settling time and with three compensators regarding the steady state error of the closed loop control system [15].

PROCESS

The controlled process is second-order-like process having the transfer function, $G_p(s)$:

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

Where:

ω_n = process natural frequency = 10 rad/s

ζ = process damping ratio = 0.05

Those process parameters represent a highly oscillating process dynamics characterized by 85.4 % maximum percentage overshoot and 7.6 s settling time.

P-D COMPENSATOR

The structure of a P-D compensator suggested to control the highly oscillating second order process is shown in Fig.1. This structure is for set-point tracking or disturbance rejection.

The proposed P-D compensator consists of two parts: a proportional controller (P-controller) in the forward path and a derivative controller (D-controller) in the feedback path. It has the sub-transfer functions $G_{c1}(s)$ for the proportional part and $G_{c2}(s)$ for the derivative part having:

$$G_{c1}(s) = K_{pc} \quad \text{and} \quad G_{c2}(s) = K_d s \qquad (2)$$

Where:

K_{pc} is the proportional gain of the compensator

K_d is the derivative gain of the compensator

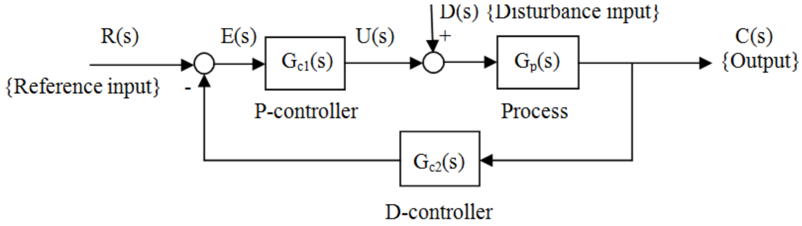

Figure1. *Process controlled by a P-D compensator*

Transfer Function of the Control System

The closed loop transfer function of the control system, M(s) is obtained using the block diagram of Fig.1 and Eqs.1and 2 and given by:

$$M(s) = (b_0) /(a_0s^2+a_1s+a_2) \quad (3)$$

Where:

$$b_0 = K_{pc}\omega_n^2$$

$$a_0 = 1$$

$$a_1= 2\zeta\omega_n + K_{pc}K_d\omega_n^2$$

$$a_2 = \omega_n^2$$

For a step reference input, R(s) = A/s, the transfer function equation (Eq3) reveals a steady state error, e_{ss} (difference between step magnitude A and steady state response c_{ss}) given by:

$$e_{ss} = A - c_{ss} = A - AK_{pc} \quad (4)$$

The P-D compensator structure makes it possible to eliminate completely the steady state error of the closed loop control system if the proportional gain of the compensator is set to one as clear from Eq.4. This leaves one compensator parameter to tune which is K_d.

P-D Compensator Tuning and Step Time Response

The P-D compensator parameter K_d is tuned as follows:

- The control and optimization toolboxes of MATLAB are used to assign the three parameters of the controller [16].
- The integral of the time multiplied by the absolute error of the control system (ITAE) is chosen as an objective function for the optimization process.
- The optimization command '*fminunc*' is used to minimize the objective function without using any functional constraints [16].
- The step response of the closed-loop control system is plotted using the command '*step*' of MATLAB [17].
- The compensator is tuned using the above approach for the underdamped second order process with 0.05 damping ratio and 10 rad/s natural frequency.
- The time-based specifications of the closed-loop control system are extracted using the MATLAB command '*stepinfo*' [18] or manually using the step time response of the control system.
- The tuned parameter of the R-D compensator is:

$$K_d = 0.3411$$

- The time response for the step tracking input using the tuned P-D compensator is shown in Fig.2 (with unit proportional gain).

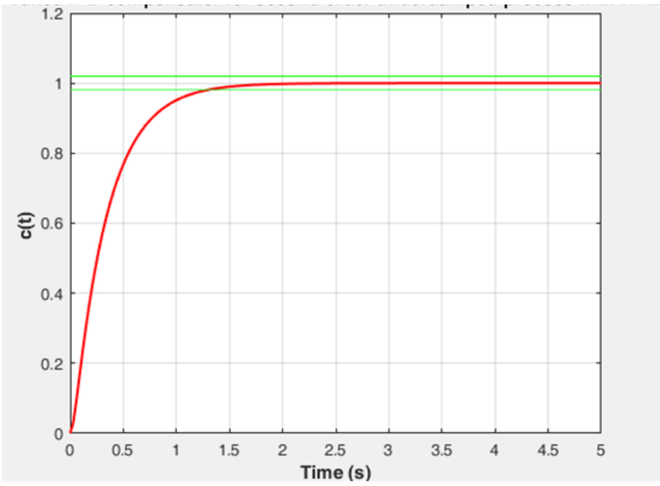

Figure2. *Unit step time response of the P-D compensator controlled second order process*

- Using the tuning technique applied in this paper, the time-based and frequency-based specifications of the closed control system incorporating the P-D compensator are as follows:

- Maximum percentage overshoot: 0 %
- Settling time: 1.23 s
- Steady-state error: 0
- Gain margin: ∞
- Phase margin: 91.7 degrees

Comparison with Minimum ITAE Standard Forms Tuning

- The parameters of the P-D compensator is tuned using the minimum ITAE standard forms of Graham and Lathrop [19]. The resulting controller parameters are:

$K_{pc} = 1$

$K_d = 0.13$

- The unit step time response of the closed loop control system incorporating the P-D compensator and the process with $\zeta = 0.05$ and $\omega_n = 10$ rad/s is shown in Fig.3. using both tuning techniques.
- The characteristics of the control system using the two tuning techniques are compared in Table 1.

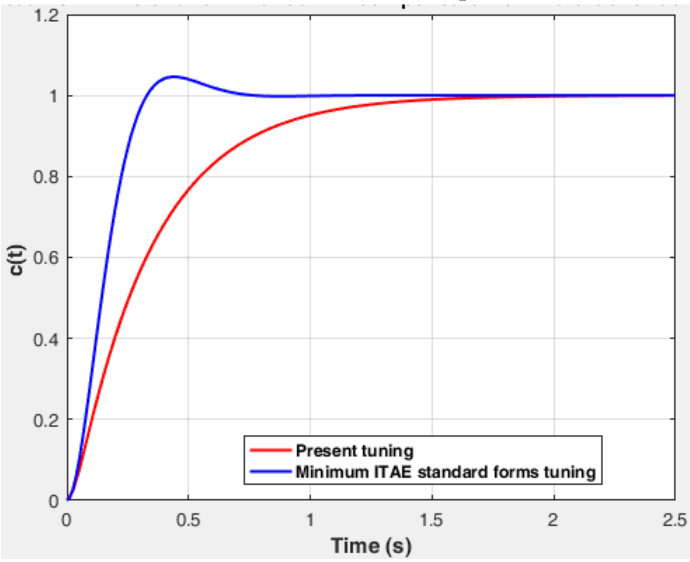

Figure3. *Unit Step Time Response Using Two Tuning Techniques*

Table1. *Characteristics Comparison using Two Tuning Techniques*

Tuning technique	Present tuning	ITAE standard forms
Maximum overshoot (%)	0	4.59
Settling time (s)	1.23	0.60
Steady state error	0	0
Gain margin (dB)	∞	∞
Phase margin (degrees)	91.70	94.40

- The present tuning technique generates a time response for step input tracking free from any overshoot.
- The minimum ITAE standard Forms generates a step time response with about 4.6 % maximum percentage overshoot.
- The ITAE standard Forms generates a step time response with 0.6 s settling time compared with 1.23 s for the present tuning technique.

Comparison with Other Compensators

The performance of the new P-D compensator presented in this paper in controlling the highly oscillating second order process for step reference input tracking is compared with one compensator from the first compensator generator and three compensators from the second generator family: feedforward lag-lead compensator [15], feedback PD compensator [1], feedforward Notch compensator [5] and feedback first order compensator [2]. The graphical comparison is shown in Fig.4.

The characteristics of the control system using one compensator from the first compensator generation and four compensators from the second generation are compared in Table 2.

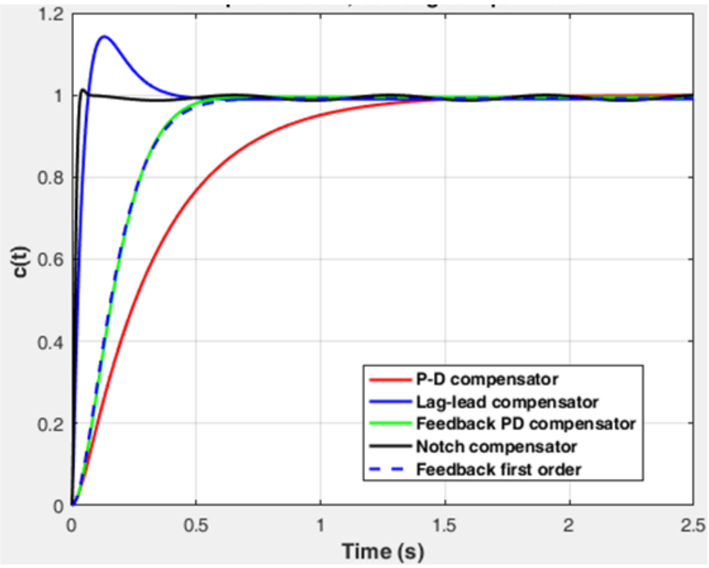

Figure4. *Unit step time response using five controlling compensators*

Table2. *Characteristics Comparison using Five Compensators*

Compensator	P-D compensator	Lag-lead compensator	Feedback PD compensator	Notch compensator	Feedback first order compensator
Maximum overshoot (%)	0	4.59	1.00	1.7588	0
Settling time (s)	1.23	0.60	0.50	0.032	0.499
Steady state error	0	0	0.005	0.0066	0.050
Gain margin (dB)	∞	∞	∞	∞	∞
Phase margin (degrees)	91.70	94.40	93.30	99.60	87.30

CONCLUSION

- A new P-D compensator was presented to control the highly oscillating second order process.
- The compensator was designated as a P-D compensator with a proportional control mode in the forward path and a derivative control mode in the feedback path.
- The new compensator has two gain parameters. One of them assigned to provide a desired steady state error for the closed loop control system for step tracking reference input.
- The second compensator parameter was assigned through compensator tuning to adjust the performance characteristics of the time response for step reference input tracking.
- The compensator was tuned using MATLAB optimization toolbox as an unconstrained single-variable optimization problem.
- The ITAE was used in the tuning technique as an objective function.
- The tuned P-D compensator could generate a step time response in reference input tracking having zero maximum overshoot and zero steady state error.
- The phase margin of the control system using the P-D compensator was 91.7 degrees which is outside the good performance range for good performance of the control system by only 1.7 degrees according to the work of Lei and Man [20].
- The tuning technique used in the paper was compared with the compensator tuning using the minimum ITAE standard forms of Graham and Lathrop [19]. The present tuning didn't exhibit any overshoot in the step reference input time response compared with 4.59 % maximum overshoot using the minimum ITAE standard forms technique. However, the settling time was halved using the minimum ITAE standard forms.
- The performance of the control system using the present P-D compensator was compared with that due to the used of four different control compensators: one from the first compensators generation and three from the second generator presented before by the author.
- The work presented in this research paper revealed some important guidelines for control engineers:

- Overshoot was cancelled completely using P-D and feedback first order compensators.
- The steady state error was cancelled completely using P-D and feedforward lag-lead second order compensators.
- The phase margin was within the range of Lie and Man [20] using the feedback first order compensator.
- The phase margin was marginal using the P-D compensator.

\- The possibility of using the P-D compensator for disturbance rejection requires further research.

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