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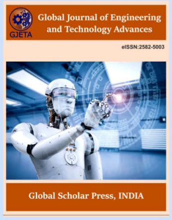

(Research Article)

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Tuning of a control compensator from the first generation with comparison with compensators from the second compensator generation

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Abstract

The paper investigates the tuning of a second order compensator from the first compensators generation when used to control a highly oscillating second order process. It compares the performance characteristics of the control system comprising this compensator to control the highly oscillating second order process with those resulting from the use of five compensators from the second compensators generation. The comparison covers three time-based characteristics: maximum percentage overshoot, settling time and steady-state error. All the compensators are tuned and the analysis results help control engineers to select appropriate compensators according to the desired performance characteristic for a specific application.

Keywords: Control compensators; Compensators generation; Compensator tuning; Highly oscillating process; Performance characteristics

1. Introduction

Automatic control is used to maintain accuracy in most industrial and domestic operations. The units used to perform control are controllers and/or compensators. Conventional compensators comprised first order and second order feedforward compensators introduced during the 1960's of the last century [1], [2]. Because of some of the drawbacks of the conventional compensators, the author conducted an intensive research to enhance the use of compensators to provide better performance for the control system during the period 2013-2015 as will be illustrated in the following literature review focusing on the use of feedforward compensators and how they are designed.

Loh, Cai and Tan (2004) tuned relays with hysteresis to determine points on the frequency response of a plant with a user specified gain and phase. Their tuning involved setting either the amplitude of the relay or its hysteresis width. They applied their technique to the auto tuning of phase lead and lag compensators [3]. Hang, Wang and Ye (2005) derived analytical tuning formulas for phase lead compensators with gain and phase margin specifications for a servo plant with an integrator [4]. Horing (2012) used a genetic algorithm to design a lead-lag compensator including the design specifications directly into the cost function or fitness function. He presented through simulation the performance of the proposed simulator [5].

Hassaan, Al-Gamil and Lashin (2013) studied the tuning of a lag-lead compensator having four parameters when used to control a first order with an integrator process. Their tuning technique could generate a step time response for reference input tracking of 2.438 % maximum overshoot and 0.648 s settling time [6]. Hassaan (2014) investigated the use of a number of compensators aiming at the improvement of control system performance when using a number of compensators for reference input tracking in what he called the second generation of compensators. He studied the use of a 2/2 second order compensator to control a highly oscillating second order process. Through tuning the

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compensator he could improve the performance of the control system achieving a zero maximum overshoot, an 0.2 s settling time and an 0.01 steady state error [7]. He studied the use of a feedback PD (proportional-derivative)compensator to control a highly oscillating second order process. Through tuning the compensator he could improve the performance of the control system achieving an 0.1 % maximum overshoot, an 0.407 s settling time and an 0.005 steady state error [8]. He studied the use of a feedforward lag-lead second order compensator to control a highly oscillating second order process. Through tuning this compensator, he could improve the performance of the control system achieving a 6.93 % maximum overshoot, an 1.41 s settling time and couldn't get rid of an initial kick [9]. He studied the use of a feedforward Sallen-Key compensator to control a highly oscillating second order process. Through tuning this compensator he could improve the performance of the control system achieving a zero maximum overshoot, an 9.3 s settling time and a steady state error less than 0.01 [10]. He studied the use of a feedback first order compensator to control a highly oscillating second order process. Through tuning this compensator he could improve the performance of the control system achieving an 0.099 % maximum overshoot, an 0.388 s settling time (using a 5 % band) and an 0.05 steady state error [11]. He studied the use of a notch compensator to control a highly oscillating second order process. Through tuning this compensator he could improve the performance of the control system achieving a zero maximum overshoot, an 0.03 s settling time and an 0.0066 steady state error [12]. He studied the use of a third order compensator to control a highly oscillating second order process. Through tuning this compensator he could improve the performance of the control system achieving an 0.35 % maximum overshoot, an 2.1 s settling time and an 0.0065 steady state error [13]. He studied the use of a second order compensator to control a highly oscillating second order process. Through tuning this compensator he could improve the performance of the control system achieving a zero maximum overshoot, a 15 s settling time and an 0.015 steady state error [14].

Hassaan (2015) presented a tuning technique to tune a feedforward first order compensator for use with a very slow second order process having 150 s settling time. Using a tuning technique based on the MATLAB optimization toolbox he could obtain a step time response to reference input tracking having zero overshoot and an 0.616 s settling time [15].Jadoon et. al. (2017) conducted a comparative analysis between five different controllers for a drug infusion system. Their simulation results confirmed the effectiveness of PI (proportional - integral) and cascaded lead controllers as the best control for this application [16]. Dogruer and Tan (2019) presented a controller design using lead and lag controllers for fractional order control systems. They minimized the error occurring in the control system using integral performance criteria. They tuned the lag and lead controllers using the MATLAB optimization toolbox [17].

Kapoulea, Tsirimokou, Psychalinosn and Elwakil (2020) presented the fractional order lead/lag compensator realization using operational transconductance amplifiers as active blocks. They used simulation results derived using the cadence IC design suite and the design kit of the Austria Mikro Systeme to evaluate the performance of the presented designs [18]. So (2021) focused on the design of an intelligent PID (proportional - integral- derivative) controller to improve the regularity response performance to disturbance in an IPID. He used a lead/lag compensatorof first order filter added to the controller to mitigate the noise. He tuned the controller parameters using the ITAE error functions using the real coded genetic algorithm and compared three other methods [19].

2. The Controlled Process

The controlled process is a highly oscillating second order 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

The process parameters provide a step response to the reference input of 85 % maximum overshoot and 7.87 s settling time.

3. The Process Control using a Second Order Compensator

The process is controlled using a feedforward second order compensator set in series with the process just before it in a control loop with unit feedback element. A conventional second order compensator a transfer function, $G_c(s)$ given by [2]:

$$G_c(s) = K_c(1+T_1s)(1+T_2s) / [(1+T_1's)(1+T_2's)] \qquad (2)$$

where: K_c = compensator gain

T_1 and T_2 = two time constants of the compensator zeros

T_1' and T_2' = two time constants of the compensator poles (related to T_1 and T_2 through the relations):

$T_1' = (1/b)T_1$ and $T_2' = bT_2$

where: b = compensator parameters

The compensator has four parameters to be tuned to adjust the performance of the closed loop control system: K_c , T_1 , T_2 , b.

3.1. Transfer Function of the Control System

The closed loop transfer function of the control system for reference input tracking, M(s) is given by [9]:

$$M(s) = (b_0 s^2+b_1 s+b_2)/(a_0 s^4+a_1 s^3+a_2 s^2+a_3 s+a_4) \quad (3)$$

where: $b_0 = K_c T_1 T_2\ \omega_n^2$, $b_1 = K_c(T_1+T_2)\ \omega_n^2$

$a_0 = T_1'T_2'$, $a_1 = T_1'+T_2'+2\zeta\omega_n T_1'T_2'$

$a_2 = 1+ 2\zeta\omega_n T_1'T_2'+ T_1'T_2'\ \omega_n^2+ K_c T_1 T_2\ \omega_n^2$

$a_3 = 2\zeta\omega_n+(T_1'+T_2')\ \omega_n^2+ K_c(T_1+T_2)\ \omega_n^2$

$a_4 = (1+K_c)\ \omega_n^2$

3.2. Compensator Tuning

The four parameters of the compensator have to be tuned to provide good performance for the process when controlled with the compensator under study. The MATLAB optimization toolbox is used through its command '*fminunc*' to minimize a performance index function of the error between the step time response of the process output and its steady state response [20]. The ISE (Integral of Square Error) performance index is used an objective function to be minimized revealing the tuned compensator parameters. The result is:

$K_c = 105.0228$, $b = 50.0057$

$T_p = 0.1362$ s , $T_z = 0.0.7271$ s (4)

The tuned parameters in Eq.4 are used with the transfer function in Eq.3 to plot the step time response of the control system using the MATLAB commands '*step*' and '*plot*' [21]. The result is shown in Fig.1.

The time based characteristics of the control system using the feedforward lag-lead compensator are as follows:

Maximum percentage overshoot, OS_{max}: 15.30 %
Settling time, T_s: 0.36 s
Steady-state error, e_{ss}: 0.0094

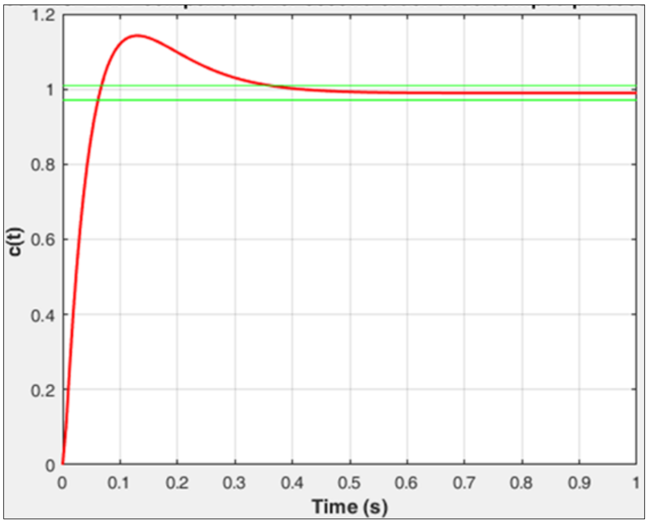

Figure 1 Step Time Response using Feedforward Lag-lead Compensator

4. The Process Control using a Feedback PD Compensator

A feedback PD compensator was a novel compensator suggested by the author in 2014 to control second order underdamped processes. The process is controlled using a feedback PD compensator set in parallel with the process. The PD compensator has a transfer function, $G_c(s)$ given by:

$$G_c(s) = K_{pc} + K_d s \quad (5)$$

where: K_{pc} = compensator proportional gain

K_d= compensator derivative gain

The compensator has two parameters to be tuned to adjust the performance of the closed loop control system: K_{pc} ,K_d.

4.1. Transfer Function of the Control System

The closed loop transfer function of the control system for reference input tracking, M(s) is given by [8]:

$$M(s) = b_0 / (a_0 s^2 + a_1 s + a_2) \quad (6)$$

where: $b_0 = \omega_n^2$

$a_0 = 1$, $a_1 = 2\zeta\omega_n + K_d\omega_n^2$

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

4.2. Compensator Tuning

The two parameters of the compensator have to be tuned to provide good performance for the process when controlled with the compensator under study. The MATLAB optimization toolbox is used through its command '*fmincon*' to minimize a performance index function of the error between the step time response of the process output and its steady state response [20]. The ITAE (Integral of time multiplied by Absolute Error) performance index is used an objective function to be minimized subjected to functional constraints on maximum percentage overshoot, settling time and steady state error of the step time response to reference input tracking. This procedure revealed the tuned compensator parameters. The result is [8]:

$$K_{pc} = 0.0050 \quad , \quad K_d = 0.1725 \quad (7)$$

The tuned parameters in Eq.7 are used with the transfer function in Eq.6 to plot the step time response of the control system using the MATLAB commands '*step*' and '*plot*' [21]. The result is shown in Fig.3.

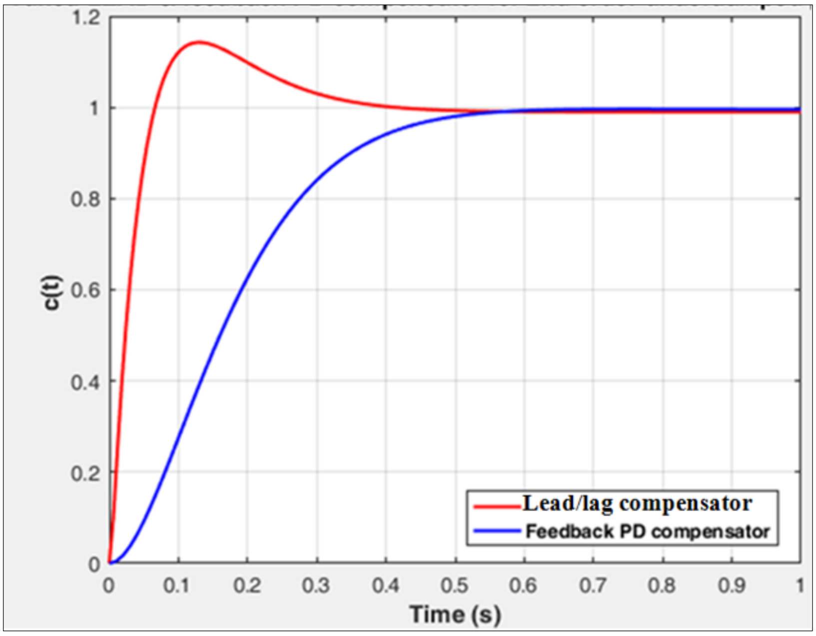

Figure 2 Step Time Response using Feedback PD Compensator

The time based characteristics of the control system using the feedback PD compensator are as follows:

- Maximum percentage overshoot, OSmax:1%(compared with 15.3 % for the second order compensator)
- Settling time, T_s: 0.5 s (compared with0.36 s for the second order compensator)
- Steady-state error, e_{ss}: 0.005 (compared with 0.0094 for the second order compensator)

4.3. The Process Control using a Feedforward Notch Compensator

In 2014 the author presented the model of a notch filter [22] to be used as a feedforward compensator to control the highly oscillating second order process [12]. The process is controlled using a feedforward Notch compensator set in series with the process just before it in a control loop with unit feedback element. The transfer function of the Notch compensator, $G_c(s)$ given by [12]:

$$G_c(s) = K_c(s^2+b_1) / [(s^2+a_1s+b_1)] \tag{8}$$

where: K_c = compensator gain

a_1, b_1 = compensator parameters

The compensator has three parameters to be tuned to adjust the performance of the closed loop control system: K_c , a_1 , b_1.

4.4. Transfer Function of the Control System

The closed loop transfer function of the control system for reference input tracking, M(s) is given by [12]:

$$M(s) = (\beta_0s^2+\beta_1)/(\alpha_0s^4+\alpha_1s^3+\alpha_2s^2+\alpha_3s+\alpha_4) \tag{9}$$

where: $\beta_0 = K_c\omega_n^2$, $\beta_1=K_cb_1\ \omega_n^2$

$\alpha_0 = 1$, $\alpha_1 = 2\zeta\omega_n+a_1$

$\alpha_2 = (1+K_c)\ \omega_n^2+ 2\zeta\omega_na_1$

$\alpha_3 = a_1\omega_n^2+ 2\zeta\omega_nb_1$, $\alpha_4 = b_1(1+K_c)\ \omega_n^2$

4.5. Compensator Tuning

The three parameters of the compensator have to be tuned to provide good performance for the process when controlled with the compensator under study. The MATLAB optimization toolbox is used through its command '*fminunc*' to minimize a performance index function of the error between the step time response of the process output and its steady state response [20]. The ITAE performance index is used an objective function to be minimized revealing the tuned compensator parameters. The result is:

$$K_c = 151.5478, \quad a_1 = 198.2830, \quad b_1 = 100.0584 \qquad (10)$$

The tuned parameters in Eq.10 are used with the transfer function in Eq.9 to plot the step time response of the control system using the MATLAB commands '*step*' and '*plot*' [21]. The result is shown in Fig.3 [12].

The time based characteristics of the control system using the feedforward notch compensator are as follows:

- Maximum percentage overshoot, OS_{max}:1.7588 % (compared with 15.3 % for the second order compensator)
- Settling time, T_s: 0.032 s (compared with 0.36 s for the second order compensator)
- Steady-state error, e_{ss}: 0.0066 (compared with 0.0094 for the second order compensator)

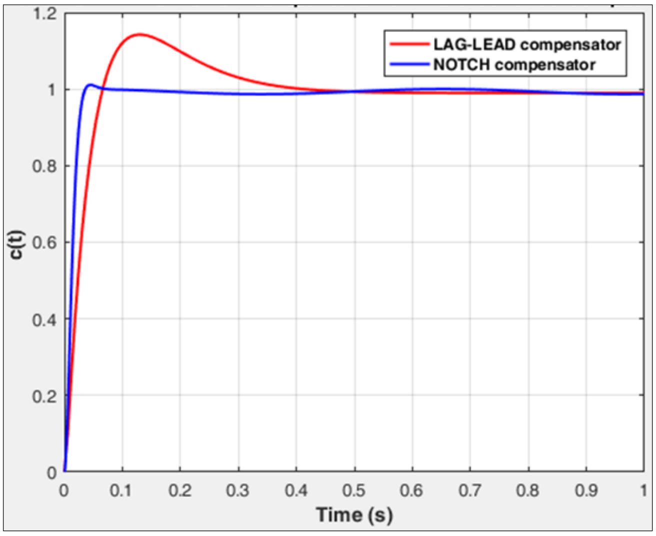

Figure 3 Step Response using Notch Compensator

5. The Process Control using a Feedback First Order Compensator

In 2014 the author presented a novel structure for a compensator composed of a proportional controller in the forward path and a feedback first order compensator to control the highly oscillating second order process as shown in Figure 4 [11].

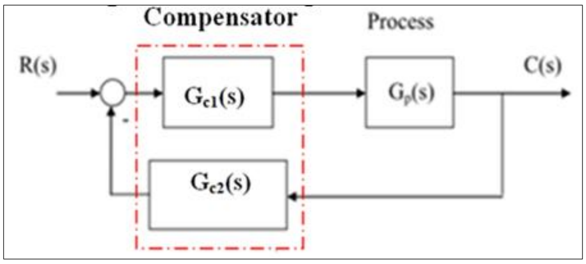

Figure 4 Block Diagram of a Control System using a novel compensator[11]

The transfer function of the compensator elements $G_{c1}$and $G_{c2}(s)$ are given by [11]:

$$G_{c1} = K_{pc} \qquad (11)$$

$$G_{c2}(s) = K_c(1+T_z s) / (1+T_p s) \quad (12)$$

where: K_{pc} = proportional controller gain

K_c = compensator gain

T_z = time constant of the compensator zero

T_p = time constant of the compensator pole

The compensator has four parameters to be tuned to adjust the performance of the closed loop control system: K_{pc}, K_c ,T_z , T_p.

5.1. Transfer Function of the Control System

The closed loop transfer function of the control system for reference input tracking, M(s) is given by [11]:

$$M(s) = (\beta_0 s+\beta_1)/(\alpha_0 s^3+\alpha_1 s^2+\alpha_2 s+\alpha_3) \quad (13)$$

where: $\beta_0 = K_{pc}T_p\omega_n^2$, $\beta_1=K_{pc}\,\omega_n^2$

$\alpha_0 = 1$, $\alpha_1 = 1+2\zeta\omega_n T_p$

$\alpha_2 = 2\zeta\omega_n+ T_p\omega_n^2+ K_{pc}K_cT_z\,\omega_n^2$

$\alpha_3 = (1+K_{pc}K_c)\,\omega_n^2$

5.2. Compensator Tuning

The three parameters of the compensator have to be tuned to provide good performance for the process when controlled with the compensator under study. The MATLAB optimization toolbox is used through its command '*fmincon*' to minimize a performance index function of the error between the step time response of the process output and its steady state response [20]. The ISE performance index is used an objective function to be minimized subjected to three functional constraints on the maximum overshoot (OS_{max}), settling time (T_s) and steady state error (e_{ss}) revealing the tuned compensator parameters. The result was [11]:

K_{pc} =0.9579 , K_c = 0.00872,

T_z = 19.7396 , T_p = 0.005 (14)

The tuned parameters in Eq.14 are used with the transfer function in Eq.13 to plot the step time response of the control system using the MATLAB commands '*step*' and '*plot*' [21]. The result is shown in Fig.5 [11].

The time based characteristics of the control system using the feedback first order compensator and the proportional controller are as follows:

- Maximum percentage overshoot, OS_{max}: 0.0 % (compared with 15.3 % for the second order compensator)
- Settling time, T_s: 0.499 s (compared with 0.36 s for the second order compensator)
- Steady-state error, e_{ss}: 0.05 (compared with 0.0094 for the second order compensator)

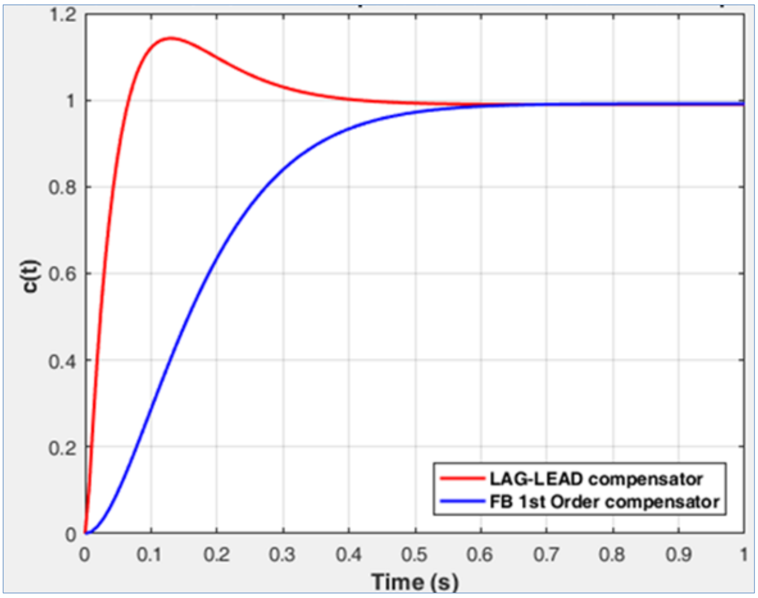

Figure 5 Step Time Response using Feedback First Order Compensator

6. The Process Control using a Feedforward Sallen-Key (SK) Compensator

A feedforward Sallen-Key compensator was a compensator suggested by the author in 2014 to control a highly oscillating second order process. The process is controlled using a feedforward SK compensator set in parallel with the process. The SK compensator has a transfer function, $G_c(s)$ given by [10]:

$$G_c(s) = K_c\, \omega_{nc}^2 / (s^2 + 2\zeta_c\omega_{nc}s + \omega_{nc}^2) \qquad (15)$$

where: K_c = compensator gain

ω_{nc}= compensator natural frequency (rad/s)

ζ_c = compensator damping ratio

The compensator has three parameters to be tuned to adjust the performance of the closed loop control system: K_c ,ω_{nc} and ζ_c.

6.1. Transfer Function of the Control System

The closed loop transfer function of the control system for reference input tracking, M(s) is given by [10]:

$$M(s) = b_0 / (a_0s^4+a_1s^3+a_2s^2+a_3s+a_4) \qquad (16)$$

where: $b_0 = K_c\omega_{nc}^2\, \omega_n^2$

$a_0 = 1$, $a_1 = 2\zeta\omega_n$

$a_2 = \omega_{nc}^2 + 4\zeta_c\zeta\omega_{nc}\omega_n$,

$a_3 = 2\zeta_c\omega_{nc}\, \omega_n^2 + 2\zeta\omega_n\omega_{nc}^2$, $a_4 = (1+K_c)\, \omega_{nc}^2\, \omega_n^2$

6.2. Compensator Tuning

The three parameters of the compensator have to be tuned to provide good performance for the process when controlled with the compensator under study. The author used a manual approach to tune the compensator revealing the following tuned compensator parameters [10]:

$K_c = 99$, $\omega_{nc} = 0.01$, $\zeta_c = 7$ (17)

The tuned parameters in Eq.17 are used with the transfer function in Eq.16 to plot the step time response of the control system using the MATLAB commands '*step*' and '*plot*' [21]. The result is shown in Fig.6.

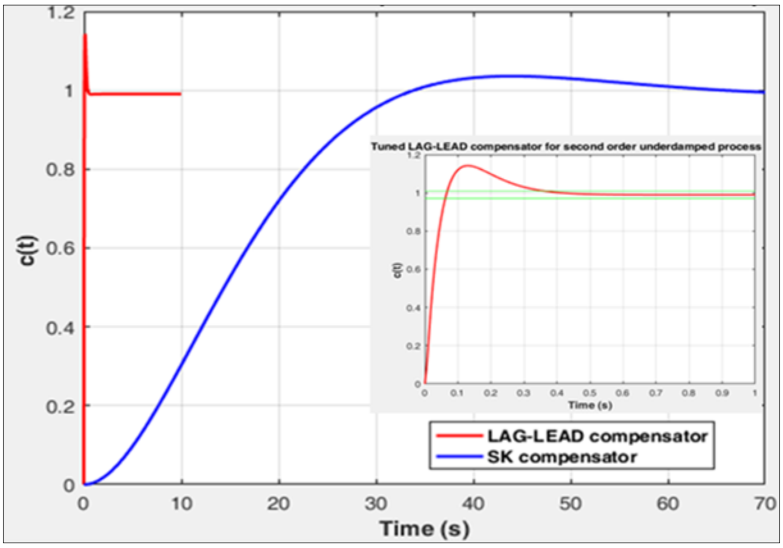

Figure 6 Step Time Response using Feedforward SK Compensator

The time based characteristics of the control system using the feedforward SK compensator are as follows:

- Maximum percentage overshoot, OS_{max}: 4.617 % (compared with 15.3 % for the second order compensator)
- Settling time, T_s: 59.8 s (compared with0.36 s for the second order compensator)
- Steady-state error, e_{ss}: 0.01 (compared with 0.0094 for the second order compensator)

7. The Process Control using a Feedforward 0/2 Second Order Compensator

A feedforward 0/2 Second Order compensator was a compensator suggested by the author in 2015 to control a highly oscillating second order process. The process is controlled using this suggested compensator set in series with the process. It has a transfer function, $G_c(s)$ given by [14]:

$$G_c(s) = K_c / (s^2 + a_1 s + a_2) \quad (18)$$

where: K_c = compensator gain

a_1 and a_2= compensator polynomial parameters

The compensator has three parameters to be tuned to adjust the performance of the closed loop control system: K_c , a_1 and a_2.

7.1. Transfer Function of the Control System

The closed loop transfer function of the control system for reference input tracking, M(s) is given by [14]:

$$M(s) = b_0 / (c_0 s^4 + c_1 s^3 + c_2 s^2 + c_3 s + c_4) \quad (19)$$

where: $b_0 = K_c \omega_n^2$

$c_0 = 1$, $c_1 = a_1 + 2\zeta\omega_n$

$c_2 = a_2 + 2\zeta\omega_n a_1 + \omega_n^2$,

$c_3 = 2\zeta\omega_n a_2 + a_1\omega_n^2$, $c_4 = (K_c+a_2)\ \omega_n^2$

7.2. Compensator Tuning

The three parameters of the compensator have to be tuned to provide good performance for the process when controlled with the compensator under study. The author used the MATLAB optimization toolbox and a set of error based objective functions to tune the compensator revealing the following tuned compensator parameters using an ITAE objective function [14]:

$$K_c = 100, \quad a_1 = 499.848 \quad , \quad a_2 = -1.160 \qquad (20)$$

The tuned parameters in Eq.20 are used with the transfer function in Eq.19 to plot the step time response of the control system using the MATLAB commands '*step*' and '*plot*' [21]. The result is shown in Fig.7.

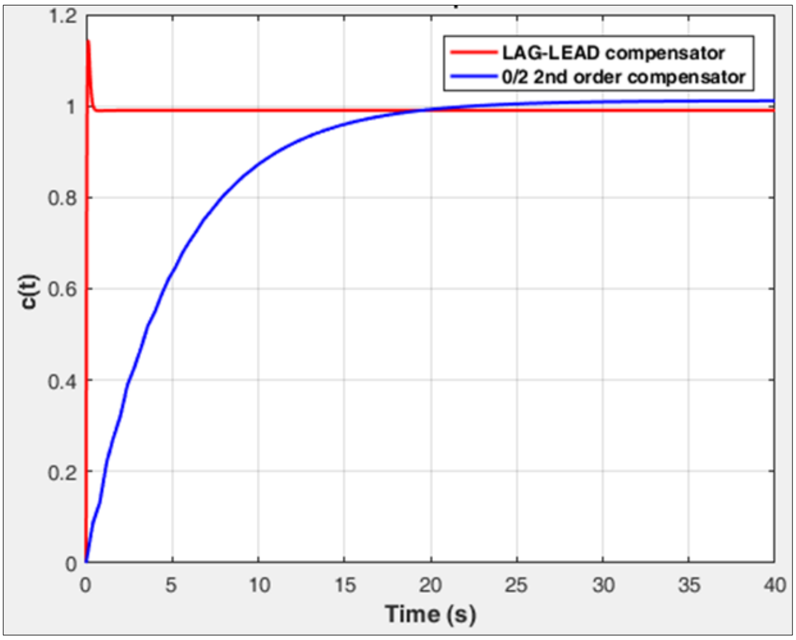

Figure 7 Step Time Response using Feedforward 0/2 Second Order Compensator

The time based characteristics of the control system using the feedforward 0/2 second order compensator are as follows:

- Maximum percentage overshoot, OS_{max}: 0.0 (compared with 15.3 % for the second order compensator)
- Settling time, T_s: 19.97 s (compared with0.36 s for the second order compensator)
- Steady-state error, e_{ss}: -0.012 (compared with 0.0094 for the second order compensator)

8. Control System Performance Comparison

The quality of any control system is judged through its performance characteristics. In this research work time-base performance characteristics were considered rather than the frequency-based performance characteristics. Six compensators are considered in this work. Their time-based performance characteristics are compared in Table 1.

Table 1 Comparison of performance characteristics of compensators

Performance Characteristics	**Maximum overshoot (%)**	**Settling Time (s)**	**Steady State Error**
Compensators			
Second Order	15.3	0.360	0.0090
Feedback Proportional - Derivative	0.10	0.500	0.0050
Notch	1.76	0.030	0.0066
Feedback First order	0	0.499	0.0500
Sallen-Key	4.62	59.80	0.0100
0/2 Second Order	0	19.97	-0.0117

9. Conclusion

A highly oscillating second order process with maximum overshoot of 85 % was considered and controlled through simulation by six compensators.

One compensator from the first generation of control compensators was used to control the process of bad dynamics.

Five compensators from the second generation of control compensators were used to control the process of bad dynamics.

The time-based performance characteristics of the control system using the six compensators were highlighted.

The step time response for reference input tracking using the compensators from the second generation of control compensators was compared with that using the second order compensator from the first generation of control compensators.

The step time response of the second order compensator from the first generation had the maximum percentage overshoot.

The Sallen-Key compensator from the second compensator generation had the maximum settling time.

The feedback first order compensator from the second compensator generation had the maximum steady-state error.

The control engineer looking for minimum maximum overshoot of the control system has to select the feedback first order and the 0/2 second order compensators from the second compensator generation where the maximum overshoot is eliminated completely.

The control engineer looking for minimum settling time of the control system has to select the notch compensators from the second compensator generation where the settling time is as low as 0.035 s.

The control engineer looking for minimum steady-state error of the control system has to select the feedback PD compensators from the second compensator generation where the steady-state error was as low as 0.005.

Compliance with ethical standards

Acknowledgments

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