Tuning of a Novel Third-order Feedforward Compensator; Part I: Used with Underdamped Second-order-like Process

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ABSTRACT
The paper presents a novel third-order feedforward compensator to control underdamped second-order-like processes. Damping ratios of 0.05 and 0.20 of the second-order-like process are considered. The proposed compensator has four parameters to be tuned to adjust the performance parameters of the closed-loop control system. The MATLAB optimization toolbox is used to solve the resulting constrained optimization problem during compensator tuning. The use of ITAE, ISE, IAE, ITSE and ISTSE objective functions is investigated. Two functional constraints are used to limit the maximum percentage overshoot and the steady-state error of the closed-loop control system. Using the proposed compensator it is possible to go down with the maximum percentage overshoot from 85.4 to 0.35 % and the settling time from 5.97 to 2.10 s for a second-order-like process of 0.05 damping ratio with ITAE objective function. Very low level steady-state error is possible using the proposed compensator.. .

Keywords *– Third-order feedforward compensator, underdamped second-order-like processes, control system performance, compensator tuning.*

I. INTRODUCTION

Highly oscillating processes represent a challenge to control engineers. The reason for this is simply the desired objective of reducing the oscillation amplitudes of the closed loop control system to minimum and to make the system as fast as possible in terms of its settling time. One of the techniques suggested by the author is using a feedforward third-order compensator. The paper studied the validity of using the feedforward compensator in conjunction with an underdamped second-order-like process.

Feced, Zervas and Muriel (1999) presented a method for the design of complex fiber Bragg gratings. They designed second-order and third-order dispersion compensators [1]. Kajita,Moon and Temes (2000) introduced an architecture for sensor interface circuit using a delta-sigma modulator. They used a third-order delta-sigma structure to shape the operational amplifier noise [2]. Boujelben, Rebei, Dallet and Marchegay (2001) presented several filter topologies suited for data conversion and measurement applications. They used a sharpened comb filter of third-order [3].

Kuntman, Cicekoglu and Ozcan (2002) described current-mode third-order Butterworth filter topologies with unity gain active elements and minimum number of passive components. They used equal values passive capacitors and resistors [4]. Aksoy, Ozcan, Cicekoglu and Kuntman (2003) presented eight current-mode third-order band pass filter topologies employing unity-gain active elements, three capacitors and three resistors [5]. Janocha, Pesotski and Kuhnen (2008) developed a method for compensating complex hysteretic actuator and sensor characteristics. They used a third-order Butterworth low-pass filter having one parameter (cutoff frequency) [6].

Casson and Villegas (2010) investigated the use of standard filter approximations for Butterworth, Chebyshev and Bessel as an alternative wavelet approximation technique [7]. Lee and Manzie (2012) proposed a technique for the attenuation of brake judder at the source. They described an adaptive compensator to establish the brake torque variation and to produce a compensating clamp force. They used first-order, second-order and third-order compensators [8]. Gan, Todd and Apsley (2013) examine the impact of time delays on emulation systems. They used first-order and third-order compensators to compensate the time delay [9].

Soi (2014) examined the design of low-pass third-order Butterworth filters of orders from one to four. He presented the electronic circuit of the third-order filter and its frequency response [10]. Iwai and Kajikawa (2015) proposed a third-order nonlinear IIR filter for the compensation of nonlinear distortions of loudspeaker systems and taking into account the self inductance nonlinearity [11]. Di et. al. (2015) presented a third-order Butterworth active RC complex band-pass filter for ZigBee transceiver applications [12].

II. PROCESS

The process used in the investigation of using the feedforward third-order compensator is a second-order one having the following 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, 0.2).

The unit step response of the process is shown in Fig.1 for the three damping ratio values.

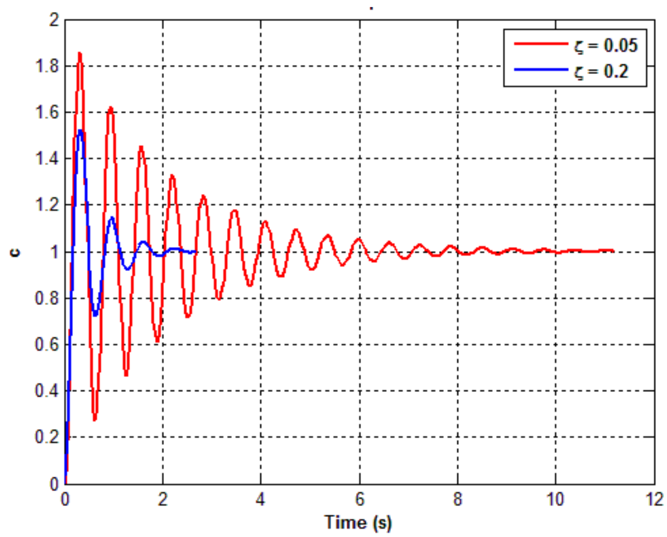

Fig.1 Process time response to a unit step input.

The time based specifications of the process for the three damping levels are given in TABLE 1.

Table 1 Process time based specifications.

Damping ratio	Maximum overshoot (%)	Settling time (s)
0.05	85.4161	5.9749
0.20	52.5701	1.3740

III. COMPENSATOR

The compensator is a third-order compensator of constant coefficients having a transfer function, $G_c(s)$ given by:

$$G_c(s) = K_c / (s^3 + a_1 s^2 + a_2 s + a_3) \qquad (2)$$

It has four parameters: K_c, a_1, a_2 and a_3. The compensator gain K_c is included to improve the steady-state characteristics of the closed-loop control system comprising the feedforward compensator and the second-order process. The other three parameters help in adjusting the performance parameters of the closed-loop control system such as the maximum percentage overshoot and the settling time.

IV. CONTROL SYSTEM TRANSFER FUNCTION

The closed-loop block diagram of the control system consists of two cascaded blocks in the forward path for the compensator [with $G_c(s)$] and process [with $G_p(s)$]. The feedback elements have unit gain, i.e. the control system is a unity feedback one. Then, the transfer function of the system, M(s) is given by:

$$M(s) = G_c(s)G_p(s)/\{1 + G_c(s)G_p(s)\} \qquad (3)$$

Combining Eqs.1,2 and 3 gives the closed loop transfer function as:

$$M(s) = K_c\omega_n^2 / \{s^5+b_1s^4+b_2s^3+b_3s^2+b_4s+b_5+ K_c\omega_n^2\} \qquad (4)$$

Where:

$b_1 = a_1+2\zeta\omega_n$

$b_2 = a_2+2\zeta\omega_n a_1+\omega_n^2$

$b_3 = a_3+2\zeta\omega_n a_2+\omega_n^2 a_1$

$b_4 = 2\zeta\omega_n a_3+\omega_n^2 a_2$

$b_5 = \omega_n^2 a_3$

V. CONTROL SYSTEM PERFORMANCE

The control system performance in the time domain is measured through [13,14]:

- Maximum percentage overshoot: For a computer-aided work, it is assigned using the MATLAB command '*Stepinfo*' for a ± 5 % of the steady state value of the time response of the closed-loop control system [15].
- Settling time for a ± 5 % band of the steady-state response of the closed-loop control system.
- Steady state error of the control system defined as the difference between the step input amplitude and the steady-state response of the system (for unity feedback control systems).

For the system transfer function given by Eq.4, the steady-state error of the system, e_{ss} is:

$$e_{ss} = a_3 / (s_3 + K_c) \qquad (5)$$

VI. TUNING THE THIRD-ORDER COMPENSATOR

The third-order compensator has four parameters to be adjusted to produce a satisfactory performance of the closed-loop control system. The tuning procedure is as follows:

1. The constrained optimization technique of MATLAB is applied through using its command '*fmincon*' [16].
2. Two functional constrains are assigned to the maximum percentage overshoot and the steady state-error.
3. Compensator parameters are constrained as follows:
   $0.01 \leq K_c \leq 200$
   $0.01 \leq a_1 \leq 500$
   $0.01 \leq a_2 \leq 500$
   $0.001 \leq a_3 \leq 2$
4. The compensator parameters are tuned through minimizing an error-based objective function (ITAE, ISE, IAE, ITSE and ISTSE) [17-21] subjected to the functional and compensator parameters constraints.
5. The compensator tuning results are given in TABLES 2-4 for a process damping ratio of 0.05, 0.2 and 0.8 respectively.

Table 2 Compensator tuned parameters and control system performance measure for $\zeta = 0.05$.

Objective function	ITAE	ISE	IAE	ITSE	ISTSE
K_c	10.6195	26.2400	1.5224	-	85.3916
a_1	5.3471	500	87.9286	-	48.6731
a_2	12.0938	189.4374	39.9132	-	48.6731
a_3	0.001	0.001	0.001	-	0.0031
OS_{max} (%)	0.3497	1	0	-	1.0044
T_s (s)	2.0830	15.4367	73.7814	-	1.3748
$10^5 e_{ss}$	9.4157	38.1080	65.6430	-	3.6026

The optimization technique with ITSE objective function did not converge to a global minimum.

Table 3 Compensator tuned parameters and control system performance measure for $\zeta = 0.20$.

Objective function	ITAE	ISE	IAE	ITSE	ISTSE
K_c	15.3171	0.3778	7.8728	200	22.9932
a_1	13.3070	107.116	499.615	10.539	7.2198
a_2	23.9766	10.500	103.888	121.32	21.9643
a_3	0.001	0.001	0.001	0.001	0.1948
OS_{max} (%)	0.7615	0.9980	1	0.9998	0
T_s (s)	3.2237	59.493	28.202	1.9061	1.7660
$10^5 e_{ss}$	6.5282	264	12.7	0.50	840

VII. STEP RESPONSE OF THE CONTROL SYSTEM

The unit step response of the control system using the tuned third-order compensator is shown in Figs. 2, 3 and 4 corresponding to the 3 damping levels of the process and the objective function used in the compensator tuning.

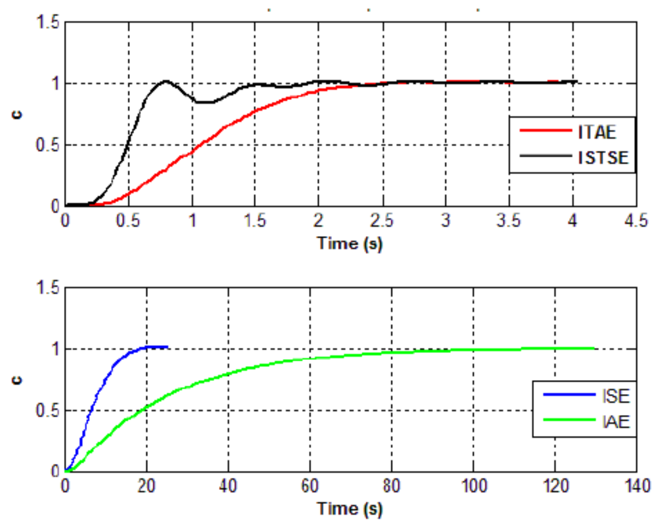

Fig.2 Time response for 0.05 process damping ratio.

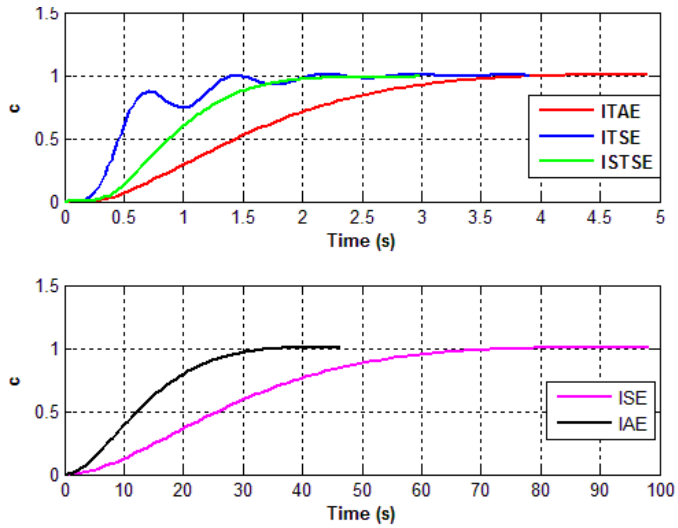

Fig.3 Time response for 0.20 process damping ratio.

VIII. CONCLUSION

- A novel third-order feedforward compensator was proposed to control underdamped second-order-like processes.
- The compensator had four parameters which were tuned using MATLAB optimization toolbox.
- The controlled second-order-like process had two levels of damping ratio (0.05 and 0.20).
- The process without any control had a step response of 85.41 , 52.57 % maximum percentage overshoot and 5.79 , 1.37 s settling time corresponding to the two damping levels.

- The proposed third-order compensator having four parameters was tuned using the MATLAB optimization toolbox.
- Five objected functions based on the error in the control system step response were used to tune the compensator (ITAE, ISE, IAE, ITSE and ISTSE).
- Using the proposed third-order compensator to control a second-order-like process of 0.05 damping ratio has reduced the maximum percentage overshoot of the closed-loop control system to only 0.35 % and the settling time to 2.10 when an ITAE objective function was used.
- Using the proposed third-order compensator to control a second-order-like process of 0.20 damping ratio has reduced the maximum percentage overshoot of the closed-loop control system to 0 % (no overshoot condition) and the settling time to 1.76 s when an ISTSE objective function was used.
- The steady-state error of te closed-loop control system using the proposed third-order compensator was as less as 65 x 10^{-5} with a second-order-like process with 0.05 damping ratio and 850 x 10^{-5} with 0.20 damping ratio process.
- The proposed third-order compensator has proven to be very efficient in generating a good-performance closed-loop control system when used with second0order-like processes having very low damping ratio.
- The proper selection of the optimization objective function had a clear impact in tuning the third-order compensator used with underdamped second-order-like processes.

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BIOGRAPHY

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