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TUNING OF A NOVEL FEEDBACK FIRST-ORDER COMPENSATOR USED WITH A HIGHLY OSCILLATING SECOND-ORDER PROCESS

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ABSTRACT

Compensators are used in place of classical PID controllers for possible achievement of better performance. Highly oscillating processes require more effort in selecting proper controllers or compensators.

In this work a novel compensator based on a series proportional controller and a feedback lag-lead compensator is proposed and applied to control a process having 85 % overshoot and about 6 seconds settling time. The proposed control scheme uses the gain constant of both the proportional controller and the feedback lag-lead compensator to control the steady-state characteristics of the closed-loop control system. The proposed controller-compensator is tuned using MATLAB optimization toolbox. It was possible with the proposed scheme to satisfy a system performance with only 0.0993 % overshoot and a settling time of 0.3886 seconds and steady-state error as low as 0.05 for a unit step input. Comparison with classical a PID tuned control was in favor of the proposed compensator.

KEYWORDS: Highly Oscillating Processes, Feedback Lag-Lead Compensator, Series Proportional Controller, Control System Performance, Compensator Tuning

INTRODUCTION

Feedforward and feedback compensators find wide application in both linear and nonlinear dynamic systems. The design of classical compensators such as lag, lead, lag-lead, PID and pre-filter are investigated in automatic control textbooks [1-5].

Lin (1965) studied designing feedback compensators by determining the minimum amplifier gain and the number of compensator poles and zeros based on the required specifications [6]. Chen and Hsu (1987) presented an approach for the design of dynamic output feedback compensators whose input signal is not one of the state variables [7]. Chung and Liu (1991) examined the exact model-matching problem for multi-input multi-output 2D linear systems using a transfer function technique. The uswed a feedback compensator of a form similar to the PID type [8].

Rosenthal (1995) introduced a compactification of the space p x m transfer functions with a fixed McMillan degree n. He investigated the pole placement problem with dynamic compensators from a geometric point of view [9]. DeBoer and Yao (2001) studied the velocity control of a double acting hydraulic cylinder utilizing a programmable valve with only cylinder pressure feedback [10]. Toosi, Ohmori and Labibi (2006) established an approach based on a sufficient condition for failure-tolerant performance stabilization in a desirable performance region under decentralized linear output feedback using genetic algorithms [11].

Kwak and Heo (2007) studied the active vibration control of a rigid structure equipped with piezoceramic sensors and actuators using multi-input multi-output positive feedback controller as an active vibration controller [12]. Jing, Mei and Hong (2008) presented an adaptive time-delay positive feedback controller for a class of nonlinear time-delay systems. Their control scheme consisted of a neural networks-based identification and a time-delay positive feedback controller [13].

Martinelli, Quandrio and Luchini (2009) provided a computationally effective formulation of the optimal feedback compensator problem. They studied the effectiveness of different objective functions, measurements and varying Reynolds number [14]. Benyong, Yanliang and Keding (2010) studied the compound control of the servo system of hydraulic flight motion simulator. Their compound control composed of a robust feedback controller and a feedforward compensator [15].

Nassirharand (2011) developed a criterion based on P or PI plus rate feedback compensator using computer-aided solution [16]. Blumthaler and Oberst (2012) investigated the stability control design by output feedback using the application of a injective cogenerator quotient signal module and quotient behaviors [17]. Wuti, Kerdpol and Bunlakananusorn (2012) presented a feedback compensator design for a two-switch forward converter. They used a PI compensator type to provide satisfactory output voltage regulation and transient response [18].

Das and Pan (2013) designed a state feedback controller with predictive gain to achieve improved performance. They used an optimization based controller design framework with linear matrix inequality constraints to ensure guaranteed stability [19]. Moraes, Castelan and Moren (2013) proposed a full-order dynamic output feedback compensator for time-stamped network control system.

They synthesized compensator gains in terms of linear matrix inequalities [20]. Rao, Raghu and Rajasekaran (2013) designed a feedback controller for a DC-DC boost converter to obtain a constant output values of the feedback controller [21]. Liu and Akasaka (2014) addressed the stabilization problem of linear systems subject to input saturation. They revealed that any linear observer can be used to realize the output feedback stabilization [22]. Zhang, Lam and Xia (2014) studied the design and analysis of output feedback delay compensation controller for network control systems. They used an output feedback strategy to generate the control input packet [23].

ANALYSIS

Process

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

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

Where

ω_n = Process natural frequency = 10 rad/s

ζ = Process damping ratio = 0.05

The time response of this process for a unit step input is shown in Figure 1 as generated by MATLAB:

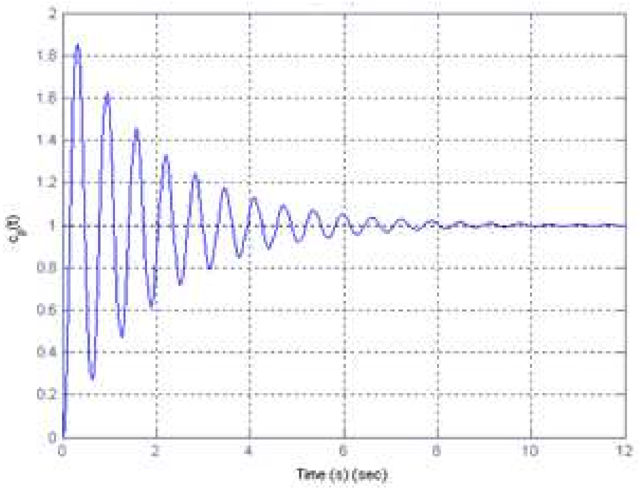

Figure 1: Step Response of Process for a Unit Step Input

The performance of the process is measured by its maximum percentage overshoot and its settling time. It has a maximum overshoot of 85.45 % and about 6 seconds settling time.

Novel Feedback Compensator

A novel feedforward proportional-controller and a feedback lag-lead compensator is proposed to control the highly oscillating second order process. The block diagram of the closed loop control system incorporating the compensator and the process is shown in Figure 2.

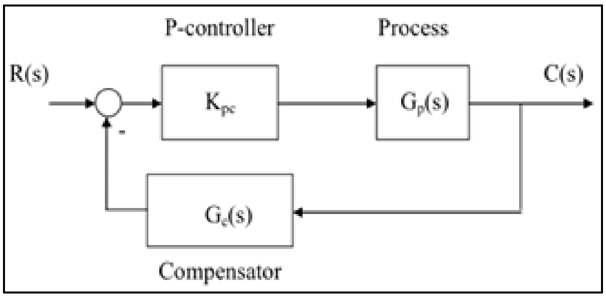

Figure 2: Proposed Control Scheme

The compensator is a first-order lag-lead type having a transfer function, $G_c(s)$ given by [5]:

$$G_c(s) = K_c(1 + T_z s) / (1 + T_p s) \quad (2)$$

It has the 3 parameters K_c, T_z and T_p which are function of the values of the resistance and capacitance of the rasistor and capacitor components encountered in the lag-lead active or passive circuit [26,28].

Control System Transfer Function

Assuming that the control system is a unit feedback one, its transfer function using Figure 2 and $G_c(s)$ of Eq.2 is:

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

where:

$\beta_0 = K_{pc}\ \omega_n^2\ T_p$

$\beta_1 = K_{pc}\omega_n^2$

$\alpha_0 = T_p$

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

$\alpha_2 = 2\zeta\omega_n + \omega_n^2 T_p + K_cK_{pc} \omega_n^2 T_z$

$\alpha_3 = \omega_n^2 (1 + K_cK_{pc})$

Stability of the Closed-Loop Control System

The compensator parameters have to be determined such that the closed-loop control system is stable. Since the closed-loop system is a third order one, it is possible to be stable. Therefore, the compensator parameters have to match the stability conditions of the control system. Using the characteristic equation which is the denominator of Eq.3 and the Routh-Hurwitz stability criterion [4,5], the stability condition is:

$$\alpha_1\alpha_2 - \alpha_0\alpha_3 > 0 \quad (4)$$

System Step Response and Performance

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 for a set of compensator parameters.

The characteristics of the compensated control system quantifying its performance are:

Steady-state response, c_{ss}:

Using Eq.3, the steady-state response of the system for a unit step input, c_{ss} is:

$$c_{ss} = \beta_1 / \alpha_3 = K_{pc} / (1 + K_cK_{pc}) \quad (5)$$

Steady-state error, e_{ss}:

Using Eq.5, the steady-state error of the system for a unit step input, e_{ss} is defined as:

$$e_{ss} = 1 - c_{ss} = (1 + K_cK_{pc} - K_{pc}) / (1 + K_cK_{pc}) \quad (6)$$

Maximum percentage overshoot, OS_{max}:

Using the time response of the control system to a unit step input, the maximum percentage overshoot is:

$$OS_{max} = 100 (c_{mas} - c_{ss}) / c_{ss} \quad (7)$$

Where:

c_{max} = maximum time response to a step input.

Settling time, T_s:

The time response of the system enters a band of ± 5 % of the steady state response and remains inside this band.

COMPENSATOR TUNING

The compensator proposed in this work is tuned using the MATLAB optimization toolbox. This optimization problem is a constrained one since functional constaints are required to control the performance of the closed-loop control system. Here, we define the objective function and the functional constraints required for the proportional controller and compensator tuning:

Objective Function

The objective function, F is taken as the integral of the se square (ISE) of the error between the stey state response of the closed-loop control system and its time response to a step input, c(t). That is:

$$F = \int [c_{ss} – c(t)]^2 \, dt \quad (8)$$

Functional Constraints

- **Maximum Percentage Overshoot**

The maximum percentage overshoot, OS has to be ≤ a specific value, OS_{des}. Thus, the first functional constraint becomes:

$$c_1 = OS - OS_{des} \quad (9)$$

- **Settling Time**

To control the speed of the closed-loop system time response, its settling time, T_s has to be ≤ a specific value, T_{sdes}. Thus, the second functional constraint becomes:

$$c_2 = T_s - T_{sdes} \quad (10)$$

- **Steady-State Error**

To control the steady-state characteristics of the closed-loop system time response, its steady-state error, e_{ss} has to be ≤ a specific value, e_{ssdes}. Thus, the third functional constraint becomes:

$$c_3 = e_{ss} - e_{ssdes} \quad (11)$$

- **Stability Constraint**

The last constraint function is relate to systemstability using the stablility condition of Eq.4. That is:

$$c_4 = \alpha_0\alpha_3 - \alpha_1\alpha_2 \quad (12)$$

Tuning Procedure

The objective function of Eq.8 is minimized subject to the functional constraints of Eqs.9-12. The functions in Eqs.8-12 are function of the controller + feedback compensator parameters which are:

$x_1 = K_{pc}$, $x_2 = K_c$

$x_3 = T_z$, $x_4 = T_p$

The 4 parameters of the controller-compensator are bounded as:

$$0.005 \le x_1, x_2, x_3, x_4 \le 100 \quad (13)$$

TUNING RESULTS

The MATLAB command "*fmincon*" is used to minimize the optimization objective function given by Eq.8 subjected to the functional inequality constraints given by Eqs. 9 through 12 and the parameters bounds of Eq.13 to provide the proportional controller - feedback compensator parameters. The results are as follows:

Controller-Compensator Parameters

K_{pc} = 0.9579, K_c = 0.00872

T_z = 19.7396, T_p = 0.00500

The time respone of the compensated system to a unit step input is shown in Figure 3.

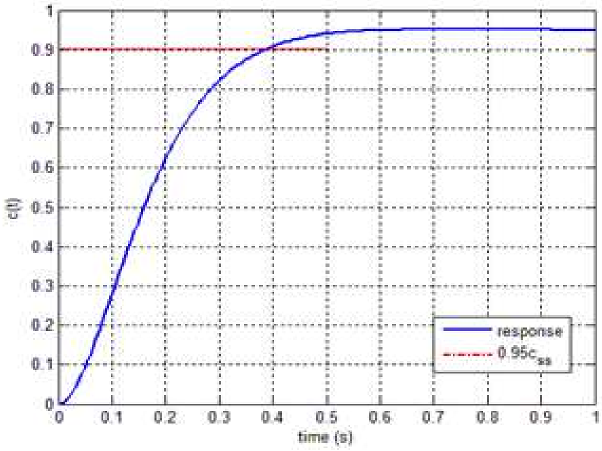

Figure 3: Step Response of the Feedback Compensated System

Characteristics of the control system using the tuned feedback compensator:

- Maximum percentage overshoot: 0.0993 %
- Maximum percentage undershoot: 0 %
- Settling time: 0.3886 s
- Steady-state error for a unit step input: 0.05

COMPARISON WITH A CLASSICAL PID-CONTROLLER

A classical PID controller is a feedforward compensator used for a long time with various linear processes[24-27]. A PID-controller used with the highly oscillating process defined by Eq.1 has an optimal parameters using an ISE objective function obtained by Hassaan as [27]:

K_{pc} = 10.0102

K_i = 9.0069

K_d = 0.6637

The time response of the PID-controlled process is shown in Figure 4:

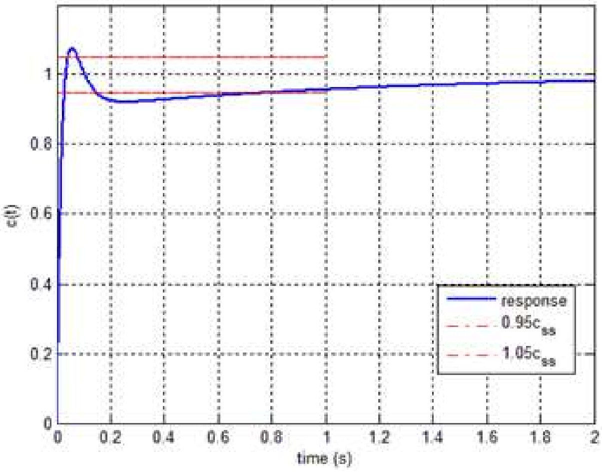

Figure 4: Step Response of the PID-Controlled Process

The haracteristics of the control system using the PID-controller are:

- Maximum percentage overshoot: 7.709 %
- Maximum percentage undershoot: 0 %
- Settling time: 0.817 s
- Steady-state error: 0

DISCUSSIONS

- The proposed feedback compensator has promising application to processes of unsatisfactory performance.
- The series P-controller is used to control the steady state characteristics of the closed-loop control system.
- Optimal tuning technique is used to tune the proposed compensator scheme.
- Through using the proposed tuning technique, it was possible to reduce the maximum percentage overshoot of uncompensated process from 85 % to 0.1 % without any undershoot.
- Using the proposed tuning technique, it was possible to reduce the settling time from about 6 seconds to 0.3886 seconds.
- Controlling the same process using a PID-controller resulted in a system time response having 7.709 % maximum overshoot (compared with 0.1 % using the proposed compensator), 0.817 s settling time (copared with 0.388 s using the proposed compensator), and zero steady-state error (compared with 0.05 using the proposed compensator).
- The optimization tuning approach used in this work is simple, straight forward, and provides the compensator parameters in a very small time using MATLAB.

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