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Disturbance Rejection Associated with a Highly Oscillating Second-order-like Process; Part I: Feedforward Second-order Compensator

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Abstract:

This paper investigates using a feedforward second-order compensator for disturbance rejection associated with a highly oscillating second-order-like process. The compensator is tuned using the MATLAB control and optimization toolboxes and five different error-based objective functions for compensator gain in the range from 5 to 25. The more suitable objective function for disturbance rejection using the second-order compensator used with the highly oscillating second-order-like process is assigned and the effect of the compensator gain on the performance of the control system in the time domain is shown. The unit step disturbance input time response of the control system has a maximum value less than 3.54, minimum value of the time response greater than -3.83 and a steady-state error as low as 0.0055 at a compensator gain of 20.

Keywords **— Disturbance rejection, delayed double integrating process, PD-PI controller, controller tuning.**

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I. INTRODUCTION

Disturbance rejection is a performance requirement associated with feedback control systems. This performance depends on the type of process to be controlled and the type of controller or compensator used. This series of research papers focuses on using specific controllers/compensators for disturbance rejection associated with one of the difficult dynamic processes which is the highly oscillating second-order process.

Skogestad (2001) presented analytic tuning rules for PID controllers resulting in good closed-loop performance. He modified the integral term of the controller to improve disturbance rejection for integrating processes [1]. Chen and Seborg (2002) proposed a design method for PID controllers based on the direct synthesis approach and specifications of the desired closed-loop transfer function. They derived analytical expressions for PID controllers controlling first-order and second-order plus time delay models. They showed that their design provided better disturbance rejection [2]. Shi and Lee (2004) presented a simple and effective tuning formulas for IMC controllers used with second-order plus dead time processes. They showed that the trade-off between set point response and disturbance rejection was limited by the normalised dead time for simple pole cases [3].

Tan, Marquez and Chen (2004) proposed criteria based on disturbance rejection and system robustness to assess PID controller performance. They showed that their criteria can be applied to stable, unstable, single-loop, multi-loop or integrating processes [4]. Jawaardhane, Logemann and Rayan (2007) investigated the efficiency of using PID control for set point and disturbance rejection in mechanical systems with hysteretic components. They determined robust conditions on the the PID gains under which tracking of constant reference signal and rejection of constant disturbance signals was guaranteed [5]. Shamsuzzoha and Lee (2008) proposed a design method for a PID cascaded with a lead-lag compensator for enhanced disturbance rejection of a second-order processes with time delay. Their proposed method illustrated greater robustness against process parameter uncertainties [6].

Liu, Yao and Gao (2009) proposed two identification methods and a united control scheme for general temperature control design. The control scheme was based on the internal-model control structure for heating up and steady operations against load disturbance. They performed examples to demonstrate the effectiveness and merit of the proposed control scheme and process identification [7]. Juneja, Ray and Mitra (2010) considered a closed-loop control system with a first-order plus dead time model and a PI controller. They demonstrated various controller design methods and tuning relations for the PI controller [8]. Xing, Donghai, Zhiqlong and Chunfeng (2011) presented a tuning method for second-order active disturbance rejection control for high performance and good robustness for a wide range of processes. They have given examples to illustrate the effectiveness and flexibility of their method [9].

Gaiduk (2012) presented a design method for automatic control systems with disturbance rejection based on Jordan controlled form (JCF) of nonlinear plants equations. The controller included state estimation of the equivalent expanded system and a number of additional investigators [10]. Agarwal (2013) developed tuning rules for PID controllers for use with unstable first-order plus dead time and second-order plus dead time processes in the form of iterative algorithms as well as in the form of accurate analytical approximations. He adapted an additional inner feedback loop design technique and designed the controller based on both gain and phase margins [11]. Rao, Subramanyam and Satyaprasad (2014) presented a PID controller with internal model control tuning method with improved IMC filter for effective disturbance rejection and robust operation of first-order process with time delay. Their suggested IMC filter provided good disturbance rejection response for process time delay < process time constant [12]. Kumar and Patel (2015) presented design approaches for 2DOF PID controllers used with undelayed second-order processes for smooth control. They obtained better results compared with PID controller for reference input tracking and disturbance rejection [13].

II. PROCESS

The process is a second-order-like process having a standard transfer function, $G_p(s)$ given by:

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

Where:

ω_n = process natural frequency
= 10 rad/s
ζ = process damping ratio = 0.05

This process is a highly oscillating process having a step response of 85.4 % maximum overshoot.

III. COMPENSATOR

The compensator is a feedforward second-order compensator proposed by the author to control the process of Eq.1 for reference input tracking [14]. The compensator has the transfer function, $G_c(s)$:

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

Where:

K_c = compensator gain.
a_1, a_2 = compensator parameters.

IV. CONTROL SYSTEM BLOCK DIAGRAM AND TRANSFER FUNCTION

The control system in case of having process disturbance has two inputs: reference input, R(s) and disturbance input, D(s). It has one output variable, C(s). The block diagram of the feedback control system incorporating the feedforward second-order compensator and the process is shown in Fig.1.

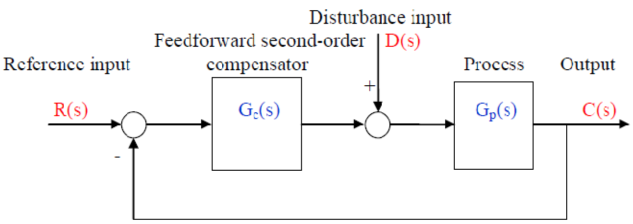

Fig.1 Block diagram of the control system.

To investigate the effectiveness of the proposed compensator in disturbance rejection, the reference input R(s) will be omitted from the block diagram, and the transfer function C(s)/D(s) will be derived.

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

$$C(s)/D(s) = (b_0s^2+b_1s+b_2)/(s^4+c_0s^3+c_1s^2+c_2s+c_3) \quad (3)$$

Where:

$b_0 = \omega_n^2$

$b_1 = \omega_n^2 a_1$

$b_2 = \omega_n^2 a_2$

$c_0 = 2\zeta\omega_n+a_1$

$c_1 = 2\zeta\omega_n a_1+ \omega_n^2+a_2$

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

$c_3 = \omega_n^2 (a_2+K_c)$

V. COMPENSATOR TUNING

Tuning of the second-order compensator allows adjusting the compensator three parameters to achieve successful rejection of the input disturbance. The desired steady-state response in this case is zero. This means that the control system has to be less sensitive to disturbance input. This allows us to define an error function e(t) as the time response to its disturbance input d(t). That is:

$$e(t) = c(t) \quad (4)$$

The first compensator parameter is its gain K_c. This parameter has a direct effect on the steady state characteristics of the control system in case of disturbance rejection as it was in the reference input tracking [14]. Therefore, K_c is kept outside the tuning process as a parameter used to control the steady-state error of the control system.

The compensator tuning for the adjustment of the other two parameters a_1 and a_2 of the compensator is performed using the error function of Eq.4 which is incorporated in an objective function to be minimized using the MATLAB optimization toolbox [15]. The objective functions used are [16]-[19]:

ITAE: $\int t|e(t)|\, dt$ (5)

ISE: $\int [e(t)]^2\, dt$ (6)

IAE: $\int |e(t)|\, dt$ (7)

ITSE: $\int t[e(t)]^2\, dt$ (8)

ISTSE: $\int t^2[e(t)]^2\, dt$ (9)

The tuning results for compensator gain of 20 with some of the specification parameters of a unit step disturbance input are given in Table 1. Relative to each other, the ISE objective function provides the best performance. Therefore, it is selected as the objective function of the tuning process of the second-order compensator used in the disturbance rejection of the highly oscillating second-order-like process.

TABLE 1
SECOND-ORDER COMPENSATOR TUNING AND CONTROL SYSTEM PERFORMANCE

	ITAE	**ISE**	**IAE**	**ITSE**	**ISTSE**
a_1	1.2045	1.1281	1.1176	1.1157	1.1015
a_2	1.1572	0.1107	0.2754	0.3054	0.4727
c_{max}	2.5105	2.3315	2.3711	2.3785	2.4272
c_{min}	-2.7187	-2.8266	-2.8209	-2.8198	-2.8147
e_{ss}	0.0547	0.0055	0.0136	0.0150	0.0231

The effect of the objective function selection of the time response of the control system for a unit disturbance input is shown in Fig.2.

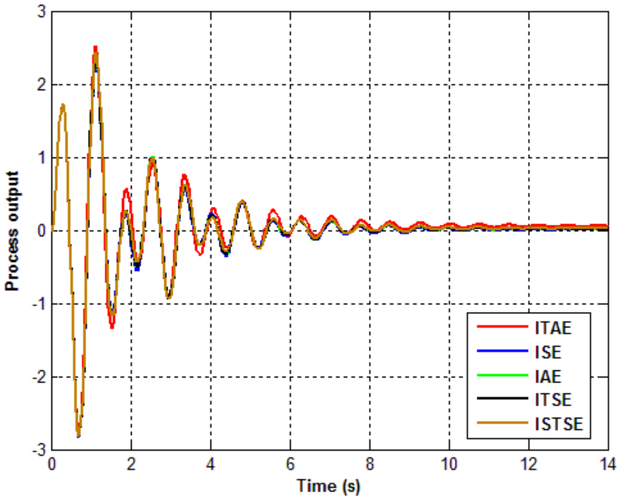

Fig.2 Unit disturbance system time response with different objective functions.

The effect of the compensator gain, K_c on the dynamic performance of the control system when disturbance rejection is the objective and using the ISE objective function is shown in Fig.3.

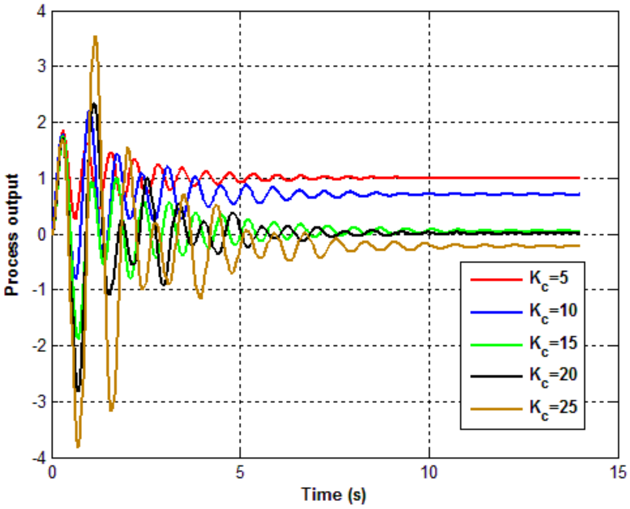

Fig.3 Effect of compensator gain on the system disturbance time response.

The effect of the compensator gain on the maximum time response, minimum time response and steady-state error of the control system due to unit step disturbance input using the ISE objective function is shown in Figs.4 and 5.

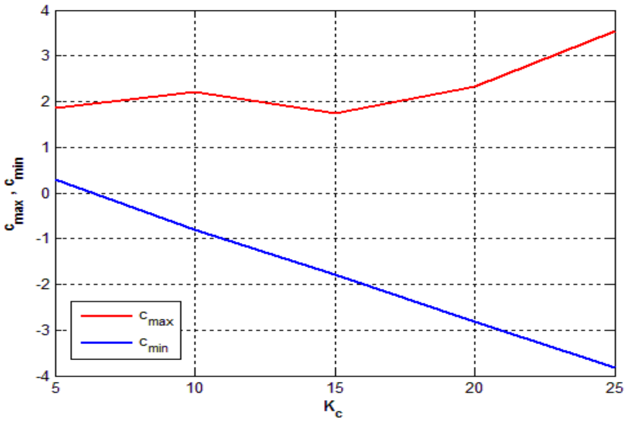

Fig.4 Effect compensator gain on the maximum and minimum process time response.

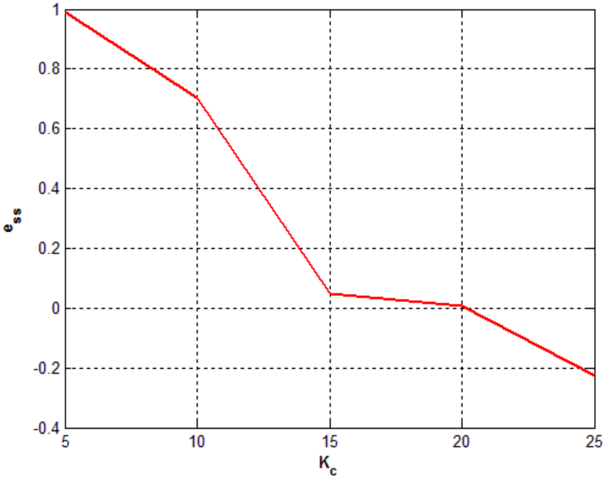

Fig.5 Effect compensator gain on the steady-state response of the control system.

VI. CONCLUSIONS

- A feedforward second-order compensated was investigated for disturbance rejection associated with delayed double integrating processes.
- The compensator had three parameters, one of them is used to adjust the steady-state characteristics of the control system, and the other two parameters are tuned for optimal performance of the control system.
- The compensator was tuned using the MATLAB control and optimization toolboxes and five different objective functions were examined.
- The time response of the control system to a unit disturbance input for all the objective functions had an oscillating nature around the desired zero value.
- Better control system performance based on time response was obtained using the ISE objective function and all the five objective functions generated a very close time response to the unit step input disturbance input.
- The effect of the compensator gain on the control system performance was investigated during disturbance rejection. It had a remarkable effect on both transient and steady-state characteristics of the control system regarding the disturbance rejection process.
- The best value of the compensator gain was 20 where it was possible to go with the disturbance to a level of 0.0055 at steady-state..
- The maximum time response of the control system was 1.74 at a compensator gain of 15 with a steady-state error of 0.047.
- The oscillating nature of the response is not desired and it represents a drawback in the application of this type of compensators.
- The effectiveness of the application of the second-order compensator will be clear when more controllers/compensators are investigated in this research series.

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