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CompensatorTuning for Didturbance Rejection Associated with Delayed Double Integrating Processes, Part II: Feedback Lag-lead First-order Compensator

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Abstract— This paper investigates using a feedback lag-lead first-order compensator to control a delayed double integrating process for the purpose of disturbance rejection. The compensator has three parameters to be tuned to provide an optimal performance for the closed-loop control system. The MATLAB control and optimization toolboxes are used to tune the compensator using five different error-based objective functions. The feasibility of using the feedback lag-lead first-order compensator is assigned through comparison with using a feedback PD compensator for the same process. It is shown that that the compensator under study can not compete with the feedback PD compensator.

Keywords—Feedback lag-lead first-order compensator; delayed double integrating process; disturbance rejection; compensator tuning; control system performance.

I. INTRODUCTION

A delayed double integrating process is one in a group of unstable processes which represent a challenge for the control engineer to select a proper controller or compensator to control such processes either for set-point tracking or for disturbance rejection. In one research track , the author investigated using six types of controllers for possible effective disturbance rejection for delayed double integrating processes. This is the second research track where the author is investigating using different types of compensators for the same purpose.

Sename (2001) presented some results about the design of observers for time–delay systems. He provided necessary and sufficient conditions to obtain unknown input observers for time-delay systems and proposed a polynomial approach allowing robust observer design for systems including unstructured uncertainties [1]. Chen and Seborg (2002) proposed a design method for PID controllers based on the direct synthesis approach and the desired closed-loop transfer function for disturbances. They designed the controller for disturbance rejection and demonstrated examples indicating the effectiveness of their approach [2]. Goforth (2004) evaluated using PID controllers and some common linear variations to PID along with parameterized loop-shaping and active disturbance rejection control. He examined the effect of adding torque disturbance, sensor noise, mechanical resonance and load changed for various control methods [3]. Exadaktylos, Taylor and Chotai (2006) motivated earlier research on model predicting control using a non-minimal state space. They showed that this design had potential performance and robustness benefits when compared to conventional MPC using a minimal state space model with observer. They established the disturbance rejection properties of the controller [4].

Chen, Zheng and Gao (2007) applied the active disturbance injection control to representative process control problems. They used a simple PD controller to control two nonlinear continuous stirred tank reactors. They coud get a good performance in the absence of an accurate model of he process [5]. Goforth and Gao (2008) proposed an active disturbance rejection control where unknown characteristics were treated as disturbance and rejected. They obtaine promising results via simulation in applying the proposed method to typical hysteresis compensation problems [6]. Dong, Kandula, Gao and Wang (2010) presented the application of an active disturbance rejection controller to an electric power assist steering system in automobiles. Their objective was to reduced the steering torque to achieve good steering feel in the process of external disturbance and system uncertainties [7]. Alcontara (2011) presented an analytical design of feedback compensators through linear control theory. His control objectives were stability and robustness for both tracking and disturbance rejection. All the compensators he used were based on the conventional PID controller with modification in its transfer function. He used techniques to improve the load disturbance response such as the γ-tuning and λ-tuning [8].

Garcia and Albertos (2013) proposed a general structure to control long time delay plants and outlined a methodology to tune the control parameters. Their scheme was equivalent to the Smith predictor but could cope with any system including unstable and integrating plants. They compared with other proposals to illustrate the performance/robustness tradeoff and the effectiveness of the tuning process [9]. Yin, Gao and Sun (2014) proposed a 2DOF control structure for a class of unstable processes with time delay based on modified Smith predictor control. They could get superior performance of disturbance rejection and good robust stability. They designed an IMC-PID controller for disturbance rejection based on internal mode control design principle [10]. Hassaan (2015) studied the control problem of controlling an unstable delayed double integrating process using feedforward and feedback first-order lag-lead compensators. Using a feedforward compensator, he investigated the effect of process time delay for time delay up to 12 s. On the other hand with feedback compensator he covered time delay only up to 0.8 s. He demonstrated the robustness and effectiveness of both compensators when used for disturbance rejection associated with delayed double integrating processes [11,12].

II. PROCESS

The process is a delayed double integrating process having the transfer function, $G_p(s)$:

$$G_p(s) = (K_p / s^2) \exp(-T_d s) \qquad (1)$$

Where: K_p = process gain
T_d = process time delay

To facilitate analyzing the control system dynamics using linear control theory, the exponential term has to be replaced by an first-order Taylor series [13]. The effect of which is Eq.2.

$$G_p(s) \approx (-K_p T_d s + K_p) / s^2 \qquad (2)$$

III. COMPENSATOR

The feedback lag-lead first-order compensator is located in the closed loop control system as shown in Fig.1. It consists of a first-order zero and a first-order pole. It has a transfer function, $G_c(s)$ given by [14], [15]:

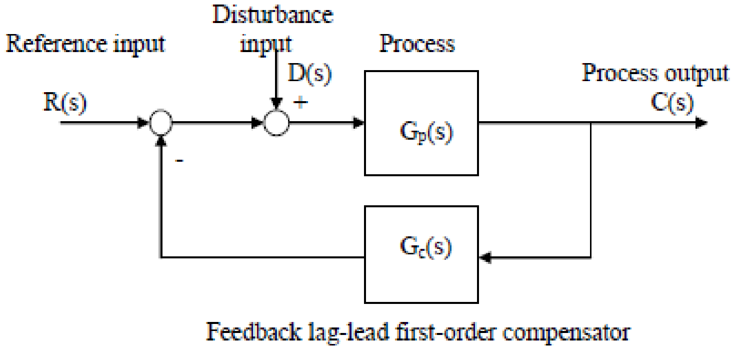

Figure 1. Control system with feedback lag-lead first-order compensator.

$$G_c(s) = K_c (1 + T_z s) / (1 + T_p s) \quad (3)$$

Where:

K_c = compensator gain
T_z = time constant of the compensator zero.
T_p = time constant of the compensator pole.

IV. CLOSED-LOOP TRANSFER FUNCTION

The closed-loop transfer function of the control system for set-point tracking (with d = 0) using the block diagram of Fig.1 and Eqs.2 and 3 is given by:

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

Where:

$b_0 = -K_p T_d T_p$
$b_1 = K_p (T_p – T_d)$
$b_2 = K_p$
$a_0 = T_p$
$a_1 = 1 - K_p K_c T_d T_z$
$a_2 = K_p K_c (T_z – T_d)$
$a_3 = K_p K_c$

The denominator of Eq.4 represents the characteristic equation of the control system. Using the Routh-Hurwitz stability criterion of the control system [16], the compensator parameters K_c, T_z and T_p can be adjusted to generate a stable control system excited by the process disturbance D(s).

V. COMPENSATOR TUNING

The feedback lag-lead first-order compensator parameters K_c, T_z and T_p have to be optimally adjusted to yield an optimal time response to the disturbance input of the control system. The controller parameters are tuned as follows:

1. The MATLAB optimization toolbox is used to minimize an objective function based on the error between the time response of the control system to a unit step disturbance input c(t) and the desired steady-state response c_{ss} which is zero in the case of disturbance rejection [17].
2. The MATLAB control toolbox is used to assign c(t) and c_{ss} [18].
3. Five objective functions are investigated through their relation with the response error e(t) as [19] – [21]:

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)

4. The optimization command '*fminunc*' is used to minimize the objective functions in Eqs.5 through 9.
5. The tuning parameters of the feedback lag-lead compensator using the five objective functions in Eq.5 through 9 have the same values given below:

$K_c = 20$
$T_z = 0.4$ s
$T_p = 0.0095$ s

6. Graphically, the unit step time response of the control system using the feedback lag-lead first-order compensator and the five objective functions is given in Fig.2.

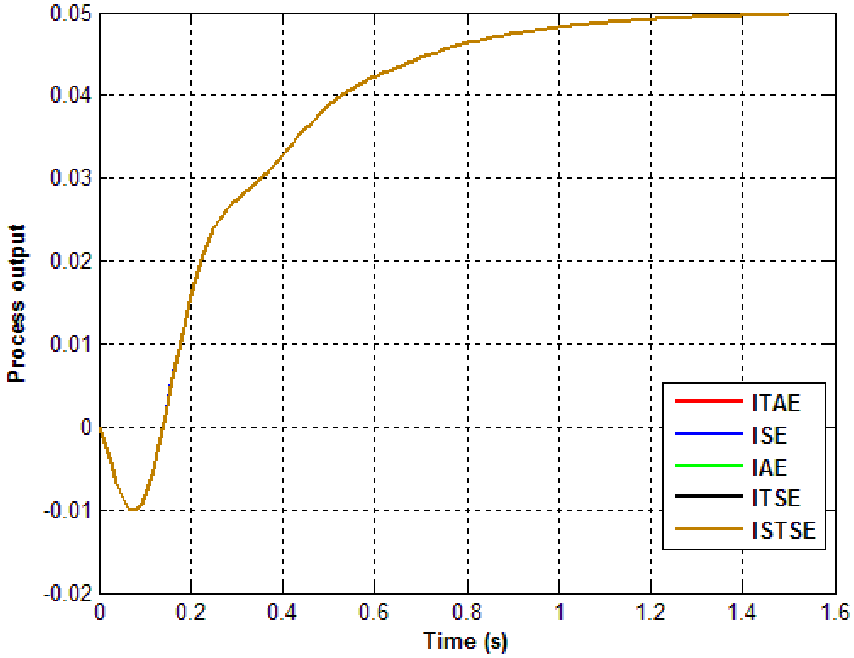

Figure 2. Time response using the five objective functions.

7. The change of the objective function has no effect on the compensator parameters, and hence on the time response to the step disturbance input as clear from Fig.2.
8. The process time delay has a remarkable effect on the dynamics of the control system when excited by the disturbance input when using the feedback lag-lead first-order compensator. Fig.3 illustrates this effect for time delay between 0.1 and 0.5 s. For time delay above 0.5 s, the time response becomes highly oscillating and the steady-state error continues increasing.

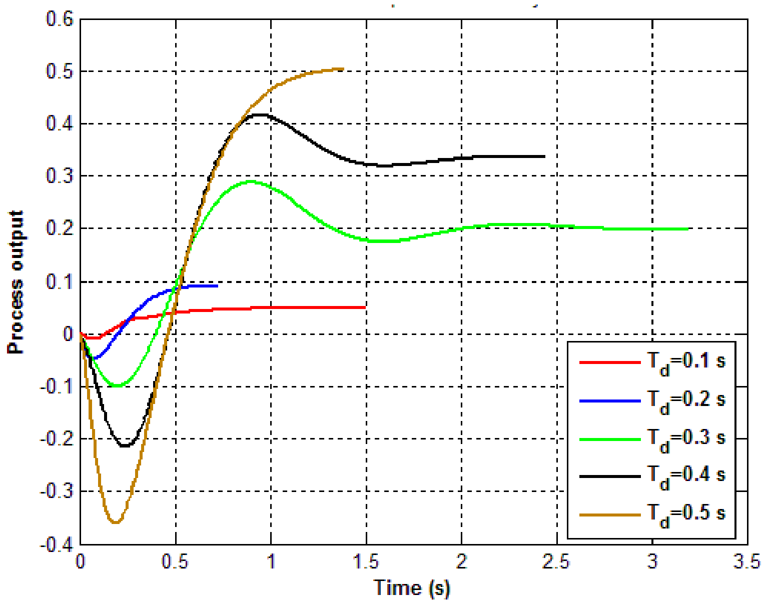

Figure 3. Effect of time delay on control system time response.

9. The effect of the of process time delay on some of the performance parameters of the closed-loop control system is shown in Figs.4 and 5. Fig.4 shows the effect on the maximum time response, c_{max}, minimum time response, c_{min} and steady-state error, c_{ss}. Fig. 5 shows the effect of the process time delay on the maximum percentage overshoot of the time response, OS_{max}. The maximum overshoot changes in the range from 0 to 44 %.

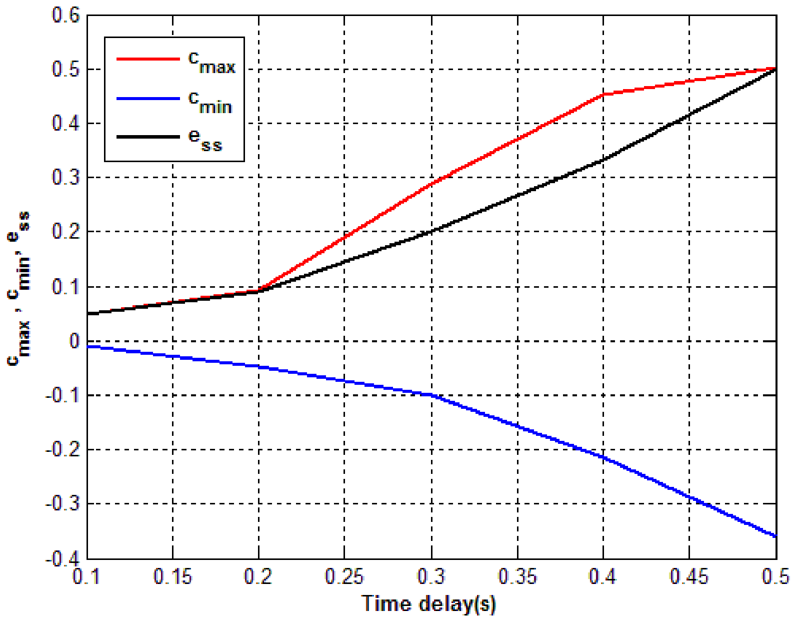

Figure 4. Effect of time delay on c_{max}, c_{min} and e_{ss}.

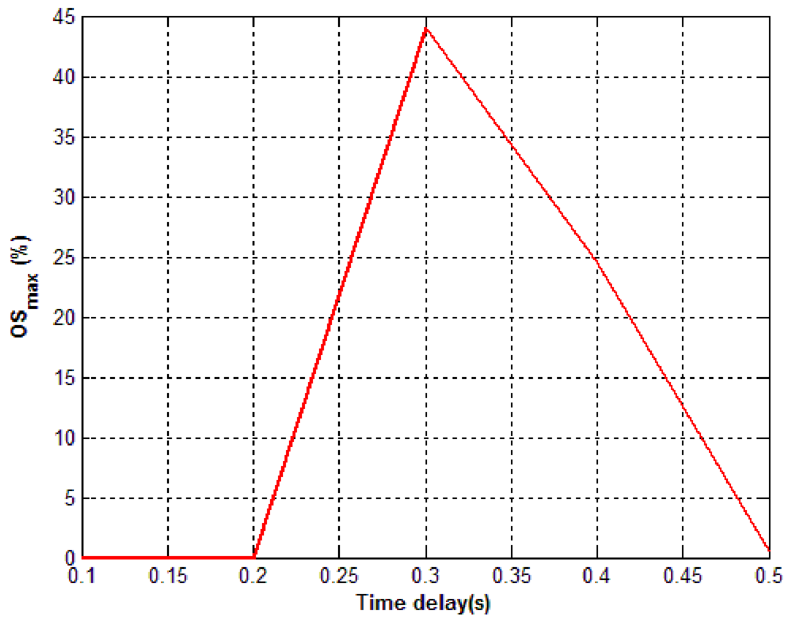

Figure 5. Effect of time delay on OS_{max}.

VI. COMPARISON WITH OTHER COMPENSATOR

To investigate the effectiveness of the proposed compensator in rejecting the disturbance associated with the delayed double integrating process, the unit step disturbance response of the closed loop control system is compared with that when using a feedback PD-compensator with the same process [..]. The comparison is presented graphically in Fig.6.

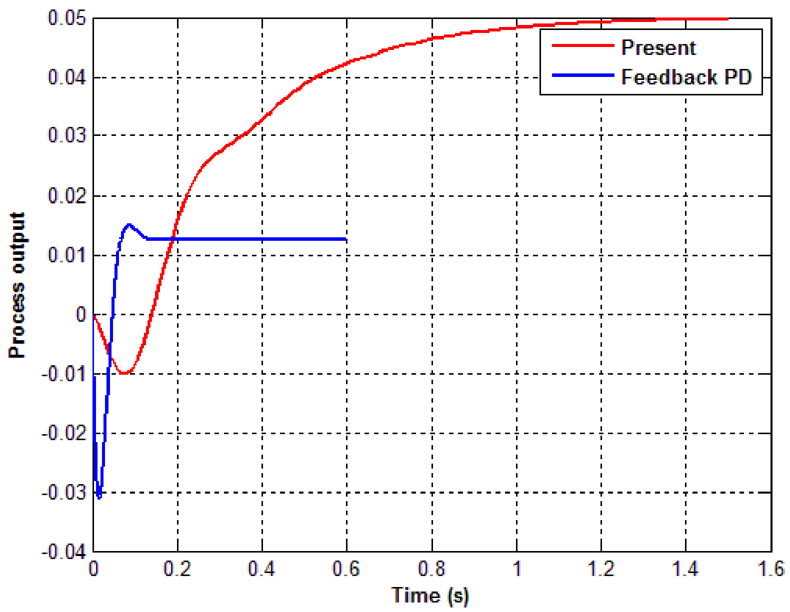

Figure 6. Performance comparison between two compensators.

VII. CONCLUSIONS

- A feedback lag-lead first-order compensator was presented to control an unstable delayed double integrating process for disturbance rejected.
- The compensator was tuned to adjust its three parameters using both MATLAB control and optimization toolboxes.
- The use of five objective functions was investigated and it has been shown that they reveal the same effect during compensator tuning.
- The time delay of the process had a major effect on the control system time response to a unit step disturbance input.
- This type of compensators could not go down to a zero steady-state response, and hence resulted in a steady-state error increased as the time delay of the process increased.
- The time response of the control system had maximum and minimum values indicating the un-evenness change of the time response.
- Comparing with the feedback PD-compensator, the feedback lag-lead first-order compensator could not compare well with the feedback PD-compensator regarding the maximum response, settling time and steady-state error.
- However, the lag-lead first-order compensator did not show any overshoot at the time delay selected and its minimum response was greater that that corresponding to the OD-compensator.

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