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COMPENSATOR TUNING FOR DISTURBANCE REJECTION ASSOCIATED WITH DELAYED DOUBLE INTEGRATING PROCESSES, PART I: FEEDBACK PD COMPENSATOR

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ABSTRACT

The purpose of this paper is to investigate the possibility of using a feedback PD compensator for disturbance rejection associated with delayed double integrating processes. The MATLAB optimization and control toolboxes are used to tune the PD compensator using five error-based objective functions. The best objective function for this control application is assigned. The effect of the process time delay on the performance of the control system during the process of disturbance rejection is investigated. The effectiveness of using the feedback PD compensator is quantitatively evaluated.

KEYWORDS: Disturbance rejection, feedback PD compensator, compensator tuning, control system performance.

INTRODUCTION

Delayed double integrating processes are a class of unstable processes which need extensive efforts in selecting proper controllers/compensators to control them for proper control system performance. The author published a series of research papers investigating using recommended types of feedforward controllers to reject disturbances associated with this difficult process. This is the first research paper in investigating a number of feedback compensators for the same purpose. The new series starts by the feedback PD compensator.

Skogestad, 2004 presented analytic rules for PID controller tuning. He improved the disturbance rejection for integrating processes through modifying the integral term of the PID controller.. Mansoor and Mansooreh, 2008 investigated a method for removing the destabilizing effects of time delay parameter in control loops. They proposed time delay compensator providing some advantages and specific properties in comparison to the conventional Smith predictor. Luca, Tian and Levy, 2008 proposed three strategies (PD, PD2 and PD3) to compensate for control packet dropout. The three strategies did not need to the of load disturbance rejection. They demonstrated illustration examples showing the improvement in load disturbance rejection. Chang, 2011 designed the disturbance rejection controller according to the estimation information of a MIMO disturbed system. His algorithm could estimate the state and the unknown disturbance and lead to avoiding the peaking phenomenon. Lin and Gao, 2011 proposed a modified IMC-based controller design to overcome sluggish load disturbance rejection associated with integrating and unstable processes with slow dynamics. Their proposed controller was based on a 2DOF control structure allowing separate optimization of load disturbance rejection. They demonstrated illustration examples showing improvement in load disturbance rejection.

Wang, 2012 reformulated the electro-hydraulic servo control problem to focus on the core problem of disturbance rejection. He developed an active disturbance rejection control solution and evaluated it against the industrial standard solution.. Afrasiabi, Monfared and Pakzad, 2013 developed a structured controller with plant input mapping approach to reach better results in predicting delay in networked control schemes. Their system performance better in higher delays but showed some weaknesses in small delay in terms of overshoot and settling time. Hassaan, 2014 proposed a feedback PD compensator to control a third-order process having 85.6 % maximum overshoot and 230 s settling time. He used an ISE objective function to tune the compensator where he could reduce the overshoot and settling time to low levels and could maintain acceptable phase margin for the closed-loop control system. Saranya and Vijayan, 2015 designed a PI controller for unstable MIMO systems using firefly algorithm. They carried out the performance assessment of the proposed controller using the heuristic methods such as firefly algorithm, particle swarm optimization and direct synthesis. They applied their technique to a two-input teo-output unstable system to demonstrate its feasibility and effectiveness. Hassaan, 2015 investigated using a PD-PI controller for disturbance rejection associated with delayed double integrating processes. He used five objective functions to tune the controller using the MATLAB optimization toolbox. He

showed that the PD-PI controller was superior in disturbance rejection of delayed integrating processes compared with conventional PID controllers.

Process

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

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

Where K_p = process gain.

T_d = process time delay.

To facilitate the application of the linear control theory to analyse control system incorporating the PD compensator and the process, the nonlinear exponential part has to be replaced with an equivalent expression as a polynomial of the Laplace operator s. Using a first-order Taylor series for the exponential term in Eq.1, it becomes [Mungan 2009]:

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

To appreciate the instability of the process defined by Eq.2, the unit step response of the process is shown in Fig.1 for a fractional time delay and a unit gain process.

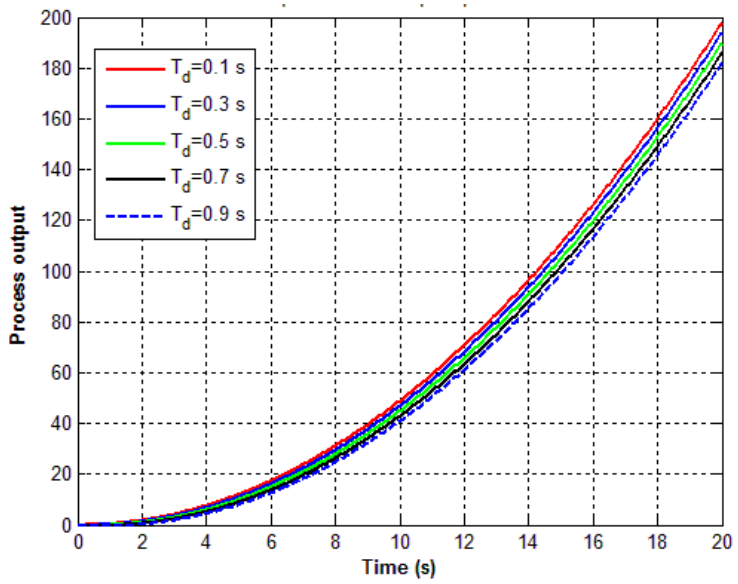

Fig.1 Unit step response of the delayed double integrating process.

Fig.1 illustrates the instability of the process and the effect of its time delay in the range: $0.1 \leq T_d \leq 0.9$ s.

Compensator

The compensator used in this study is a feedback PD compensator. This compensator was recommended before by the author to control a third-order process [Hassaan, 2014]. The block diagram of the closed-loop control system having a reference input, disturbance input and process output is shown in Fig.2.

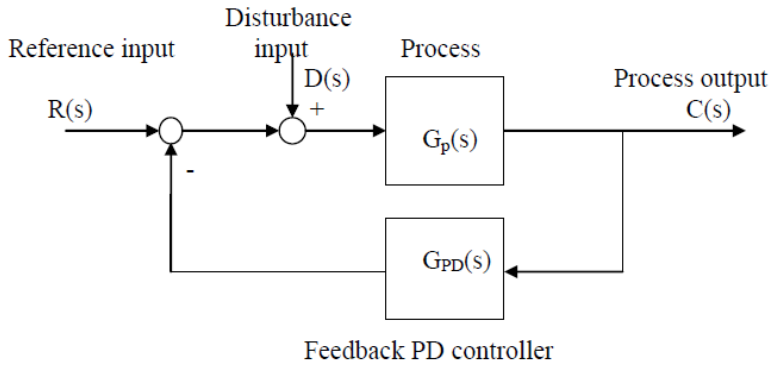

Fig.2 Control system block diagram with PD compensator.

The PD compensator is a standard PD controlling unit having the transfer function, $G_{PD}(s)$:

$$G_{PD}(s) = K_{pc} + K_d s \quad (3)$$

Where:

K_{pc} = the proportional gain of the compensator.

K_d = the derivative gain of the compensator.

Closed-loop Transfer Function

For sake of disturbance rejection study, only the disturbance input in the block diagram of Fig.2 will be considered and the reference input will be discarded. Doing this, the transfer function of the resulting control system using the feedback PD-compensator and the delayed double integrating process, C(s)/D(s) will be:

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

Where:

$b_0 = -K_p T_d$

$b_1 = K_p$

$a_0 = 1 - K_p K_d T_d$

$a_1 = K_p K_d - K_p K_{pc} T_d$

$a_2 = K_p K_{pc}$

Even the control system is a second order one, however, it is possible for the control system to be unstable because of the coefficients of s^2 and s in Eq.4 which may be negative. The conditions for a stable control system are derived from the Routh-Hurwitz criterion [Dorf and Bishop, 2008]. Applying the Routh-Hurwitz criterion on the characteristic equation of the control system (denominator of Eq.4) reveals the following limits for the PD-compensator parameters:

$$\left.\begin{aligned} & K_d < 1/(K_p T_d) \\ \text{And} \quad & K_{pc} < K_d/T_d \end{aligned}\right\} \qquad (5)$$

The compensator parameters limits equation (Eq.5) helps during the tuning process of the compensator providing an initial guess for parameter producing a stable control system against the process parameters K_p and T_d.

Compensator Tuning

- The PD-compensator is tuned, first, by the definition of an error based functions (objective functions) as follows [Patra et.al. 2013, Karnavas and Dedousis 2010, Hussain et.al. 2014]:

$$\text{ITAE:} \quad \int t|e(t)| \, dt \qquad (6)$$

$$\text{ISE:} \quad \int [e(t)]^2 \, dt \qquad (7)$$

$$\text{IAE:} \quad \int |e(t)| \, dt \qquad (8)$$

$$\text{ITSE:} \quad \int t[e(t)]^2 \, dt \qquad (9)$$

$$\text{ISTSE:} \quad \int t^2[e(t)]^2 \, dt \qquad (10)$$

- The objective function will be a nonlinear function in the compensator parameters K_{pc} and K_d and the process parameters K_p and T_d.
- The MATLAB control toolbox is used to assign the step response of the control system to a unit disturbance input for any assigned process and compensator parameters using its command '*step*' [Lopez, 2014].
- The error function e(t) is defined as the difference between the time response of the control system c(t) to unit disturbance input and the desired response (which is zero in this case)
- The MATLAB toolbox is used to define one of the objective functions in Eqs.6 to 10 using its command '*fminunc*' [Lopez, 2014].

- The tuning results for a process unit gain and a time delay of 0.1 s and some of the performance characteristics of the control system disturbance response are give in Table1.

Table 1: PD compensator tuning parameters and system characteristics.

	ITAE	ISE	IAE	ITSE	ISTSE
K_{pc}	79.9565	80.0059	80.0383	79.9688	79.9826
K_d	10	8.9627	8.9461	9.8172	9.7831
c_{max}	0.0499	0.0314	0.0316	0.0325	0.0313
t_{cmax}	0	0.1584	0.1600	0.0148	0.0166
e_{ss}	0.0125	0.01249	0.01249	0.0125	0.0125

- The effect of using five different objective functions on the compensator tuning process and the performance of the control system in response to a unit disturbance input is shown in Fig.3.

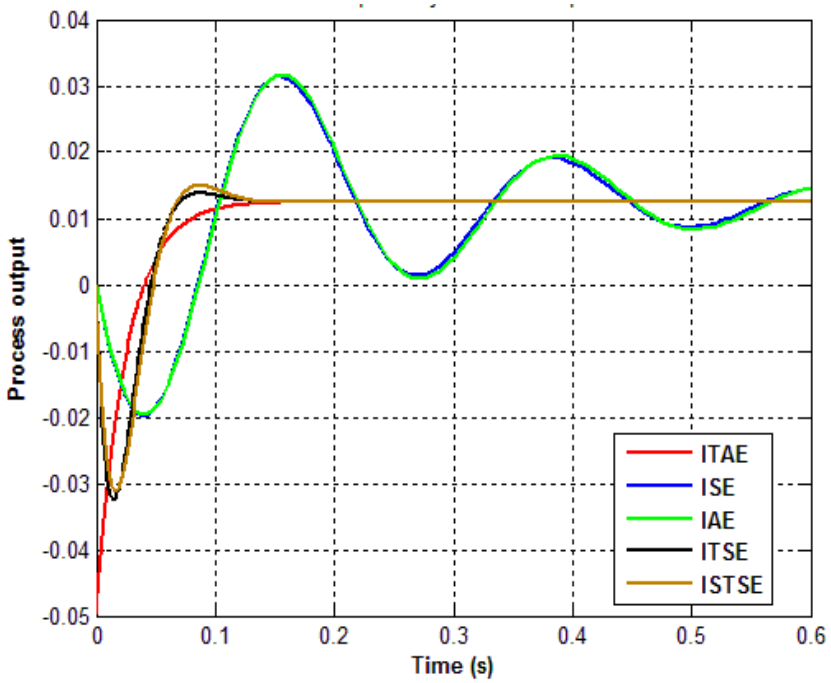

Fig.3 Effect of objective function on system time response for 0.1 s time delay.

It is clear that some objective functions provide better time response than another. All objective functions provide steady-state error of about 0.0125 depending on the value of the compensator proportional gain K_{pc}.

- The effect of the process time delay in the range $0.1 \leq Td \leq 0.9$ s on the time response of the control system for a unit disturbance input is shown in Fig.4.

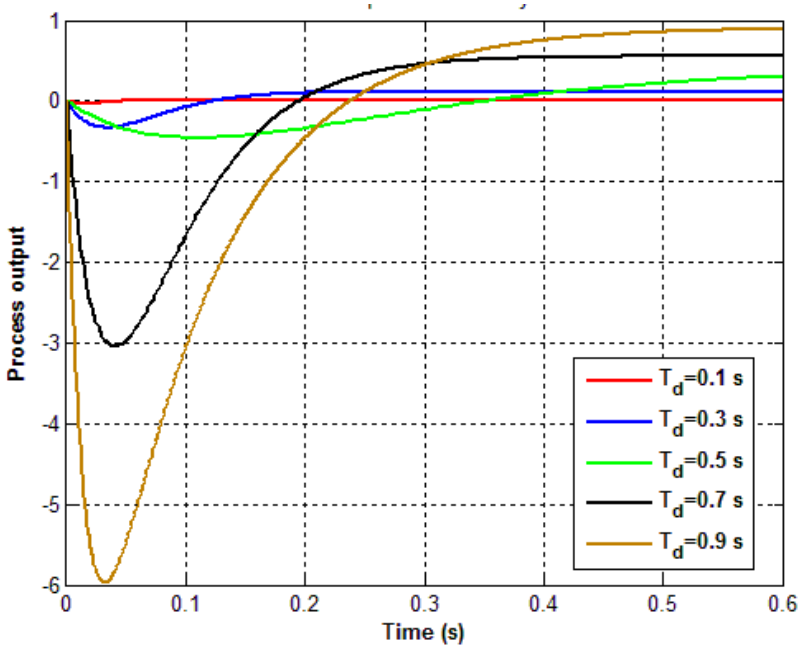

Fig.4 Effect of process time delay on disturbance time response.

There is a great effect of the process time delay on the disturbance step response of the control system. As the time delay increases, the maximum time response increases and the steady-state error also increases.

- The effect of the process time delay on the performance measures (maximum time response and steady-state error) is shown in Fig.5 for the same time range of Fig.4.

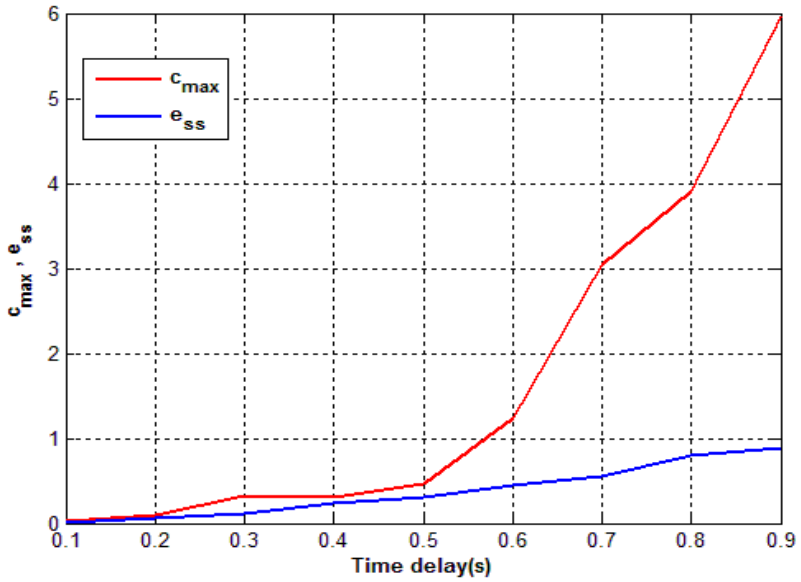

Fig.5 Effect of process time delay on maximum time response and steady-state error.

CONCLUSION

- The objective of this research work was to investigate using a feedback PD-compensator for disturbance rejection associated with unstable delayed double integrating processes.
- The compensator was tuned using the MATLAB control and optimization toolboxes.
- Five objective functions based on the error between the disturbance time response of the closed-loop control system and the desired steady-state value were used to tune the compensator.
- A process time delay between 0.1 and 0.9 s was used in the simulation study.
- The ISE and ISTSE objective functions have given the best results during the controller tuning process..
- Using a PD-compensator is expected to generate a steady-state error in the control system time response. This error was in the range of ≤ 0.03 for time delay ≤ 0.5 s.
- The maximum time response due to a unit disturbance input was ≤ 0.46 for time delay ≤ 0.5 s.
- For a process time delay ≤ 0.2 s, the maximum time response is ≤ 0.1 and the steady-state error is ≤ 0.055.
- It is possible to achieve better performance of the control system under disturbance excitation by using another types of compensators as will be studied in the rest of this research work.

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BIOGRAPHY

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