Controller Tuning for Disturbance Rejection Associated with Delayed Double Integrating processes, Part IV: PID Plus First-Order Lag Controller

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Abstract
This series of research work investigates tuning some specific controllers for possible use in disturbance rejection associated with delayed double integrating process which have nonlinear characteristics. This paper presents a PID plus first-order lag controller which has four parameters to be tuned. The MATLAB optimization toolbox is used to tune the controller using five types of error-based objective functions. The effect of process time delay between 0.1 and 3 seconds on the performance of the control system during disturbance rejection is investigated. The performance of the control system during disturbance rejection is compared with that obtained using other controllers such as PIDF, PD-PI, IPD and PI-PD controllers.

Keywords
Disturbance rejection, Delayed double integrating process, PID plus first-order lag controller, Controller tuning, Control system performance, MATLAB optimization toolbox.

I. Introduction

Dealing with process disturbance rejection is an important matter in control engineering. Not all types of controllers can succeed in achieving this objective. The aim of this series of research papers is to investigate controllers (or compensators) that are efficient in reducing the disturbance effect on the dynamics of the control system.

Skogestad (2001) presented tuning rules for PID controllers for slow response with acceptance disturbance rejection. He considered pure time delay, integrating, integrating with delay and lag and double integrating processes [1]. Skogestad (2003) presented analytic tuning rules for PID controller. He modified the integral term to improve disturbance rejection for integrating processes. He considered first-order, second-order, pure time delay, integrating, integrating with lag and double integrating processes [2]. Arvanitis, Pasgianos and Kalogeropoulos (2005) presented simple methods for tuning three-term controllers for dead-time processes. The applied the tuning methods on delayed first-order, delayed second-order, delayed single integrating, delayed double integrating and delayed two poles and single zero processes [3]. Arbogast and Cooper (2007) presented a set of IMC tuning correlations for PID with filter controller for integrating processes. They studied four forms of the PID with filter controller: ideal, interacting, parallel and parallel interacting [4].

Arvanitis, Pasgianos and Kalogeropoulos (2007) presented simple methods for identification and controller tuning of double integrating processes with dead time. They considered a PID-like controller in series form and a second-order set-point pre-filter [5]. Shamsuzzoha and Lee (2008) proposed a PID controller cascaded with first-order lead/lag filter for integrating and first-order unstable processes with time delay. They used the IMC criterion having a single tuning parameter to adjust the performance and robustness of the controller [6]. Saravanakumar and Wahidabanu (2009) designed a dead-time compensator with minimum tuning parameters, simple tuning and robust performance providing critically damped system for fast set point and load disturbance rejection performance [7]. Michal, Premont, Pillonnet and Abouchi (2010) presented a detailed overview of the circuits for PID controllers with single active element. They used a PID controller with derivative filtering as a modification for the standard PID controller [8]. Patra and Khuntia (2011) studied the tuning of some PID controller architecture including the ideal PID controller, the classical PID controller and the non-interacting PID controller [9].

Matausek and Ribic (2012) used a PID controller in series with a second-order filter defined by the dead time and an adjustable parameter. They tuned the controller for robustness and sensitivity to measurement noise. They claimed excellent performance / robustness trade-off for stable, integrating and unstable processes [10]. Herbst (2013) studied using active disturbance rejection control for its single tuning and robustness against process parameters variations. He examined the effect of the process time delay up to 0.1 s on the dynamic performance of the control system incorporating active disturbance rejection control and a delayed first-order process [11]. Hassaan (2014) used a PID with first-order lag controller to solve the dynamic problem of highly oscillating processes. He could reduce the maximum overshoot to 15.9 % and the settling time to 0.55 s through tuning the controller using an ISE objective function [12]. Hast (2015) Presented tuning of SISO and MIMO PID controllers based on convex optimization, He used set point weighing to improve the set point change response. He examined the structure of a decoupled feedback / feedforward control system for load disturbance rejection [13].

II. Process

The process used in this analysis is a delayed double integrating process having the transfer function, $G_p(s)$ *[14]*:

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

Where:

K_p = process gain
T_d = time delay of the process.

To facilitate the dynamic analysis of the control system incorporating a delayed process, the exponential term in Eq.1 has to be replaced by a polynomial in the Laplace operator s. Using the first-order Taylor series for $\exp(-T_d s)$, Eq.1 becomes *[15]*:

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

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III. Closed-Loop Control System

The block diagram of the closed loop linear control system incorporating a feedforward controller and a process is shown in Fig.1 for a reference input R(s) and a disturbance input D(s). The control system output is C(s).

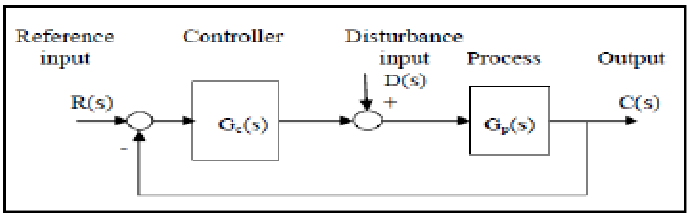

Fig.1: Block diagram of the control system with two inputs.

To study the control systems dynamics for disturbance rejection, the reference input in Fig.1 is set to zero and the new block diagram of the system becomes as shown in Fig.2.

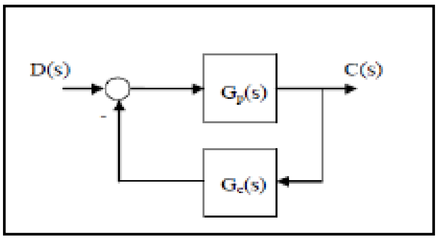

Fig.2: Block diagram of the control system with one input.

A PID plus first-order lag controller has the transfer function *[16]*:

$$G_p(s) = [K_{pc} + (Ki/s) + K_d s][1/(1 + Ts)] \qquad (3)$$

Where:

K_{pc} = proportional gain
K_i = integral gain
K_d = derivative gain
T = time constant.

The closed-loop transfer of the control system of Fig.2 for disturbance rejection, M(s) is:

$$M(s) = (b_0 s^3 + b_1 s^2 + b_2 s) / (a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4) \qquad (4)$$

Where:

$b_0 = -TT_d K_p$
$b_1 = TK_p - T_d K_p$
$b_2 = K_p$
$a_0 = T$
$a_1 = 1 - T_d K_p K_d$
$a_2 = K_p K_d - T_d K_p K_{pc}$
$a_3 = K_p K_{pc} - T_d K_p K_i$
$a_4 = K_p K_i$

IV. Controller Tuning for Disturbance Rejection

The PID plus first-order lag controller has four parameters required to be adjusted to produce accepted control system performance for a disturbance input. The MATLAB optimization toolbox is used to tune the controller parameters through the minimization of an error-based objective function *[17]*.

The ITAE, IAE and ITSE objective functions are used in the controller tuning process (*[18]-[20]*). The optimal controller parameters and some of the time based specifications of the system unit disturbance time response are given in Table 1 for an 0.1 s time delay.

Table 1 : Tuned controller parameters and performance measures for 0.1 s delay time

	ITAE	IAE	ITSE
K_{pc}	0.1291	0.1126	1.6741
K_i	0.0050	0.0037	0.3417
K_d	0.9982	0.9995	0.9030
T (s)	0.0982	0.0981	0.1057
C_{max}	5.8274	6.6471	0.8314
T_{cmax} (s)	14.5676	16.9954	2.3322
T_s (s)	62	75	13

The unit step disturbance time response of the control system for an 0.1 s time delay is shown in Fig.3.

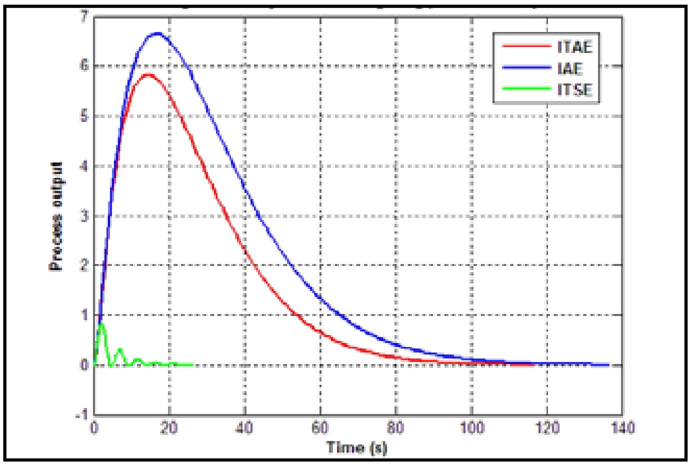

Fig. 3: Unit step disturbance response for 0.1s delay.

The ITSE objective function gives minimum time response and hence the best disturbance rejection. However, it failed to maintain a stable control system for time delay greater than 0.1 s. It was possible to get minimum response due to disturbance input when using the ITSE objective function for time delay ≤ 0.1 s. The effect of time delay on the time response during this time delay range is shown in Fig.4 using the ITSE objective function.

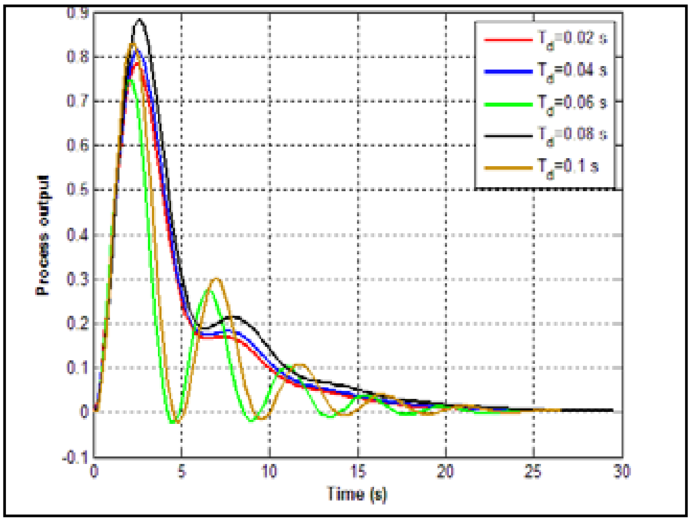

Fig.4: Effect of time delay on system time response using ITSE objective function.

For time delay ≥ 0.1 s and up to 3 s, the ITAE could give good results compared with using the IAE objective function. The time response of the control system due to a unit disturbance input is shown in Fig.5 for time delay between 0.2 and 1 s.

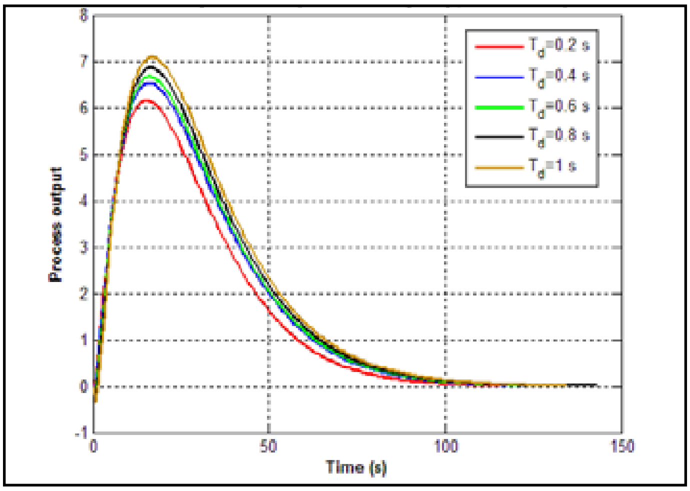

Fig. 5: Effect of time delay on system time response using ITAE objective function.

The effect of process time delay on the maximum time response, time of maximum time response and settling time of the control system time response is shown in Fig.6.

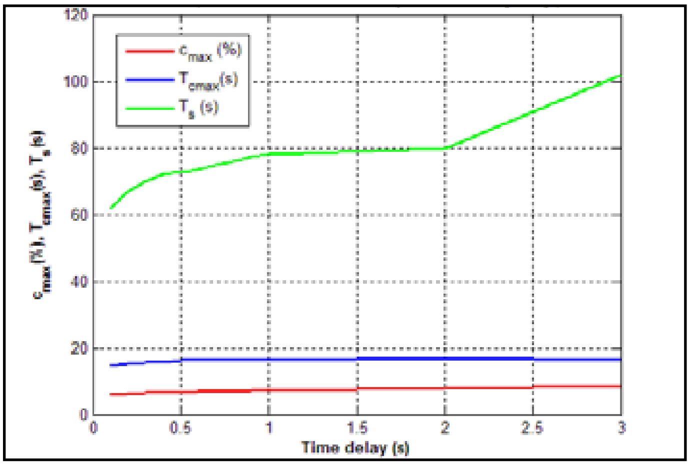

Fig.6 : Effect of time delay on performance parameters.

V. Comparison with Other Research Work

The effectiveness of the PID plus first-order lag controller is judged through comparison with other controllers used with the same double integrating process as follows:

1. For an 0.1 s time delay

The unit disturbance input time response of the control system using PD-PI, I-PD, PI-PD and the present controllers is shown in Fig.7.

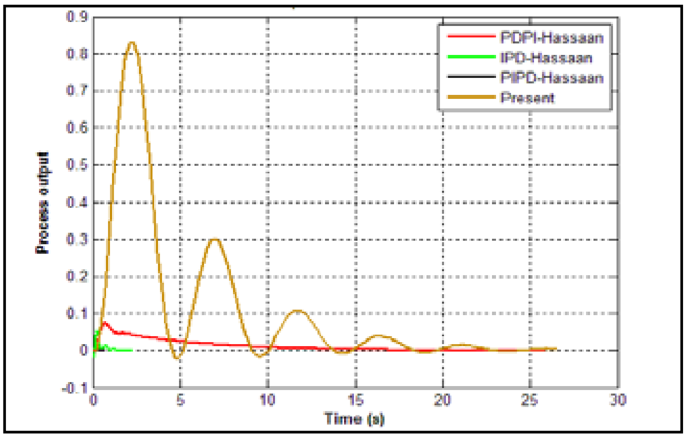

Fig. 7: Unit disturbance time response for 0.1 s time delay

The performance parameters for maximum time response, time of maximum response and settling time are compared in Table 2.

Table 2 : Performance comparison for 0.1s time delay.

	c_{max}	T_{cmax} (s)	T_s (s)
PI-PD [21]	0.0018	0.1704	0
I-PD [22]	0.0535	0.2721	0.3
PD-PI [23]	0.0735	0.7178	1.2
Present	0.8314	2.3322	13

2. For an 1 s time delay:

The unit disturbance input time response of the control system using PD-PI, PIDF, I-PD, PI-PD and the present controllers is shown in Fig.8.

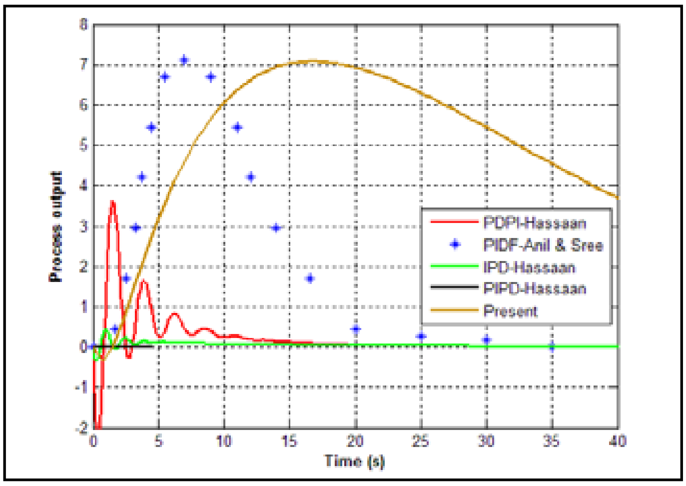

Fig. 8: Unit disturbance time response for 1 s time delay

The performance parameters for maximum time response, time of maximum response and settling time are compared in Table 3.

Table 3 : Performance comparison for 1s time delay.

	c_{max}	T_{cmax} (s)	T_s (s)
PI-PD [21]	0.026	0.047	0
I-PD [22]	0.431	1.010	15
PD-PI 23]	3.619	1.509	19
PIDF [24]	7.100	7.000	32.5
Present	7.0828	16.450	78

It is clear from the comparisons in Figs.7 and 8, Tables 2 and 3 that the PID plus first-order lag can not compete with other types of controllers specially the PI-PD, I-PD and PD-PI controllers.

VI. Conclusions

- The use of a PID plus first-order lag controller for disturbance rejection associated with a delayed double integrating process was investigated.
- The controller was tuned using MATLAB optimization toolbox.
- The effect of using three objective functions in the controller tuning process was investigated.
- The effect of process time delay on the performance parameters has been shown for time delay up to 3 seconds.
- The performance of the control system using the PID plus first-order lag was compared with that using another four types of controllers used with the same process at unit time delay and unit gain.
- This type of feedforward controllers failed to compete with the other types of controllers.

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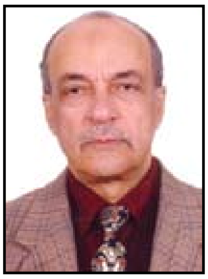

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