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Controller Tuning for Disturbance Rejection Associated with Delayed Double Integrating Process, Part III: PI-PD Controller

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Abstract

The problem of tuning a PI-PD controller for used with an unstable delayed double integrating process for disturbance rejection is studied. The effect of time delay of the process in a range between 0.1 and 2 seconds is considered. The controller is tuned using MATLAB optimization toolbox with five forms of the objective function in terms of the error between the step time response of the closed-loop control system. Using the proposed controller with the delayed double integrating process indicates the effectiveness and robustness of the PI-PD controller in the time delay range used with superior time-based specifications compared with other techniques based on using PIDF, IPD and PD-PI controllers with the same process.

Keywords –*PI-PD controller, Delayed double integrating process, Controller tuning, Control system performance, Controller robustness.*

I. INTRODUCTION

Delayed double integrating processes are examples of unstable processes which require extensive efforts in proper selection of suitable controllers or compensators and also looking for proper tuning techniques to achieve stable control system and accepted performance.

Merkin and Zhang (2001) presented the parameterization of stabilizing 2DOF controller for possible unstable processes with dead-time. They applied the proposed method to integral processes with dead-time to obtain the sub-ideal disturbance response [1]. Kaya (2003) showed that in some situations, improved set point and disturbance responses can be obtained bu using PI-PD controller. He presented some examples to illustrate his approach [2]. Hangin (2003) studied the control system design for time-delayed unstable processes and for periodic disturbance rejection. He used PID control, IMC-based PID control and modified Smith predictor control [3].

Majhi and Mahanta (2004) proposed a fuzzy PI-PD controller tuned by genetic algorithm and had self-tuned gains. Their results demonstrated better transient performance using the proposed fuzzy PI-Pd controller [4]. Kaya and Atherton (2005) suggested a cascade control structure and controller design based on standard forms for controlling integrating processes in a cascade control structure [5]. Wang, Zhang and Wang (2006) investigated using a PI-PD controller on the basis of particle swarm optimization to decrease peak overshoot, maximum undershoot, settling time and rise time of non-minimum phase system. They compared their approach with genetic algorithm simulated annealing PID controller [6]. Pail and Kuo (2008) presented a speed control scheme for a 2-mass motor drive system. They proposed two kinds of hybrid fuzzy PD/PI for the speed control problem. They showed that their proposed controller can track effectively the desired speed in the presence of load disturbance [7].

Tan (2009) presented a graphical method for the computation of all stabilizing PI-PD controllers by plotting the stability boundary locus. His method was used to design robust PI-PD controllers for control systems with parametric uncertainties [8]. Matusu and Prokop (2010) studied the comparison of different continuous-time strategies applied to control SISO periodically time varying systems with delay. They use a modified PI-PD Smith predictor for control processes with long dead time tuned using ISE and ITSE objective functions [9]. Pedro and Dahunsi (2011) presented he design of a neural network based feedback linearization controller for a 2DOF quarter-car, servo-hydraulic vehicle suspension system. They compared the proposed controller with a PID controller based on Ziegler-Nichols tuning method during suspension travel setpoint tracking in the presence of road disturbance [10].

Liu and Gao (2012) presented step response of identification methods for integrating and unstable processes using open-loop or closed-loop step test. They studied two 2DOF control schemes for set point tracking and load disturbance rejection for stable, integrating and unstable processes [11]. Sundaram and Padhy (2013) proposed a GA-based PI-PD controller for active queue management. They tuned the controller using an ISTE objective function. They demonstrated the practical advantage of using GA-based PI-PD controller over the PI controller [12]. Hassaan (2014) used a PI-PD controller to control a highly oscillating second-order process. He tuned the controller using an ISE objective function through using the MATLAB optimization toolbox. He could cancel completely the overshoot of the step time response of the control system and reduce the settling time to only 0.35 second [13]. Ali (2014) presented a design of robust PI-PD position controller for magnetic levitation ball system. He used the particle swarm optimization method to tune the controller. He demonstrated the effectiveness of the PI-PD controller experimentally and by simulation [14]. Saranya and Vijayan (2015) designed PI controller for unstable MIMO systems using firefly algorithm. They examined the feasibility and effectiveness of their proposed method using a 2-input 2-output unstable system [15].

II. PROCESS

The controlled process is delayed double integrating process having the transfer function, Gp(s):

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

Where K_p is the process gain and T_d is its time delay. It is dealt with the exponential term in Eq.1 through the first-order Taylor series as [..]:

$$\exp(-T_d s) \approx 1 - T_d s \qquad (2)$$

Combining Eqs.1 and 2 gives the process transfer function as:

$$G_p(s) = (-K_p T_d s + K_p) / s^2 \qquad (3)$$

The unit step response of the process using Eq.3 is shown in Fig.1.

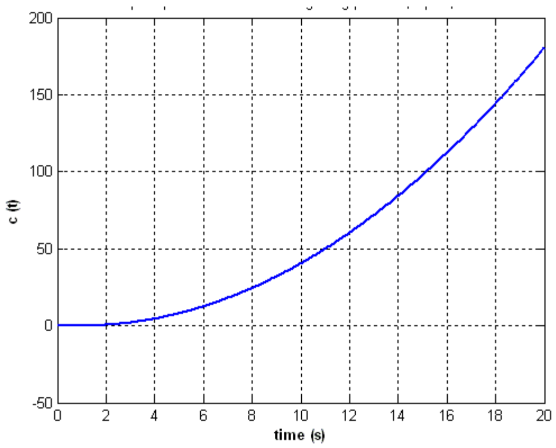

Fig.1 Step response of the double integrating process.

It is clear from Fig.1 that the double integrating process is an unstable 1. The controller has to generate an stable feedback control system and also to achieve an accepted performance when rejecting a process disturbance through tuning the controller.

III. CLOSED-LOOP CONTROL SYSTEM

The controller used is a PI-PD controller with inputs from the reference input of the control system and its output. The structure of the controller is shown in Fig.2 in a control system having both reference and disturbance inputs. [16,17]. The disturbance input in Fig.2 is added by the author.

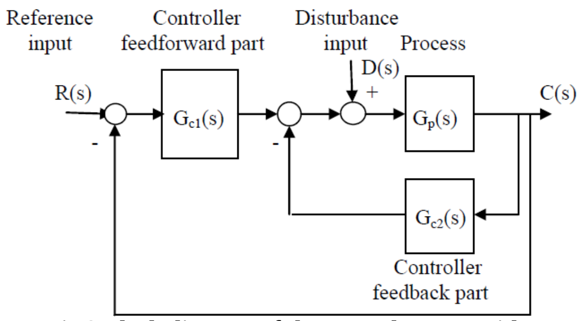

Fig.2 Block diagram of the control system with two inputs.

The PI-PD controller has two parts:

- Feedforward part having an input which is the error R(s) – C(s) and a transfer function G_{c1}:

$$G_{c1} = K_{pc}[1 + (\tau_i s)^{-1}] \qquad (4)$$

Where:
K_{pc} = proportional gain of the controller.
τ_i = integral time constant of the controller

- Feedback part having an input which is the system output C(s) and a transfer function G_{c2}:

$$G_{c2} = K_f(1 + \tau_d s) \qquad (5)$$

Where:
K_f = feedback gain of the controller.
τ_d = derivative time constant of the controller

This means that the PI-PD controller has four parameters to be tuned for proper control system performance: Kpc, Kf, τ_i and τ_d.

For purpose of studying disturbance rejection, only the disturbance input D(s) will be considered as a control system input and the reference input R(s) of Fig.2 will be omitted. The resulting block diagram of the closed-loop control system is shown in Fig.3.

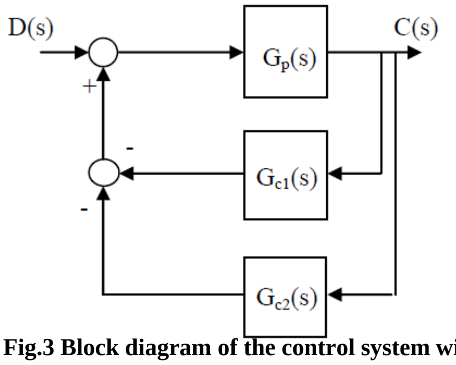

Fig.3 Block diagram of the control system with disturbance input.

IV. CONTROL SYTEM TRANSFER FUNCTIONS

The closed-loop transfer function of the control system, M(s) for the control system with disturbance input is obtained using the block diagram of Fig.3 and given by:

$$M(s) = (b_0s^2 + b_1s) / (s^3 + a_0s^2 + a_1s + a_2) \quad (6)$$

Where:

$b_0 = -K_pT_d$
$b_1 = K_p$
$a_0 = K_fK_p\tau_d - K_fK_pT_d$
$a_1 = K_fK_p + K_{pc}K_p - K_{pc}K_pT_d/\tau_i$
$a_2 = K_{pc}K_p/\tau_i$

V. PI-PD CONTROLLER TUNING AND SYTEM TIME RESPONSE

The controller has to be tuned to achieve two purposes:

(i) Providing a stable closed-loop control system.
(ii) Controlling the performance of the closed-loop control system in terms of efficient rejection of the disturbance effect on the system output (magnitude and time).

The PI-PD controller parameters are tuned as follows:

- The optimization toolbox of MATLAB is used for this purpose [18].
- The MATLAB command *'fminunc*' is used [18].
- A number of objective functions based on the error between the step time response of the control system and its steady-state response are selected to tune the compensators. They are ITAE, ISE, IAE, ITSE and ISTSE [19-22].
- The tuning procedure is applied for a specific time delay of the double integrating process in the range $0.1 \le T_d \le 2$ s.
- The step response of the closed-loop control system is plotted for a unit step disturbance input using the command '*step*' of MATLAB [23].
- The time-based specifications of the control system are extracted using the MATLAB command '*stepinfo*' [23].

A sample of the tuning results is shown in Table 1 for an 0.1 s time delay of the double integrating process and a unit gain.

Table 1: PI-PD controller tuning for process unit gain and 0.1 s time delay.

Objective Function	K_{pc}	K_f	τ_i (s)	τ_d (s)
ITAE	20.021	1.282	0.961	3.180
ISE	65.192	9.911	0.766	0.446
IAE	142.113	140.958	0.612	0.553
ITSE	1034.80	0.396	0.267	89.941
ISTSE	27.437	1.268	0.885	5.410

The time response of the control system for a unit step disturbance input is shown in Fig.4 for time delay of 0.1 s.

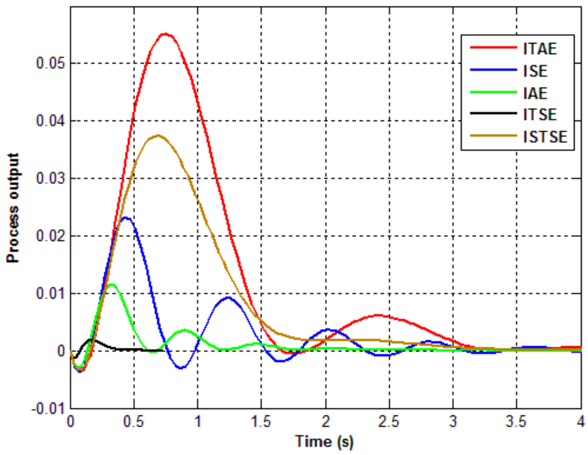

Fig.4 Control system time response for an 0.1 s time delayed double integrating process.

Varying the type of the optimization objective function has remarkable affect the time response of the control system. This means that there is a specific objective function providing the best tuning of the PI-PD controller parameters to minimize the sensitivity of the control system to the disturbance input.

The effect of the process time delay on the disturbance step response of the control system incorporating the delayed double integrating process is shown in Fig.5.

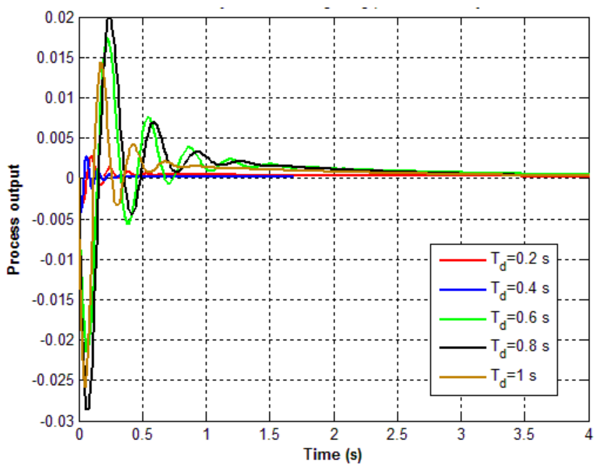

Fig.5 Effect of the process time delay of system time response.

The response level is very small (less than 0.02) for the process time delay range between 0.1 and 2 s. This means that this controller is very efficient in suppressing the system disturbance over the other types studied before by the author [24,26].

The effect of the time delay of the double integrating process on some of the time-based specifications of the control system due to disturbance input is shown in Fig.6.

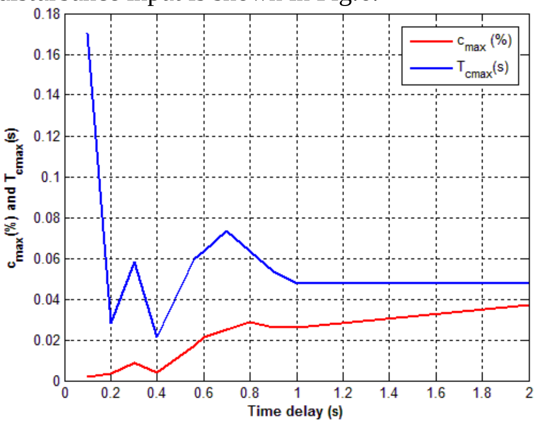

Fig.6 Effect of process time delay on maximum time response and time of maximum response.

The maximum time response almost increases as the time delay increases. The time of maximum response almost decreases as the time delay increases. The settling time of the time response is zero for time delay range covered in this research study.

VI. COMPARISON WITH OTHER RESEARCH WORK

The unit time response of the control systems as presented in the present work using a PI-PD controller is compared with the research works using PD-PI controller [24], PIDF controller [25] and IPD controller [26] for the same delayed double integrating process having unit gain and unit time delay. The comparison is presented graphically in Fig.7.

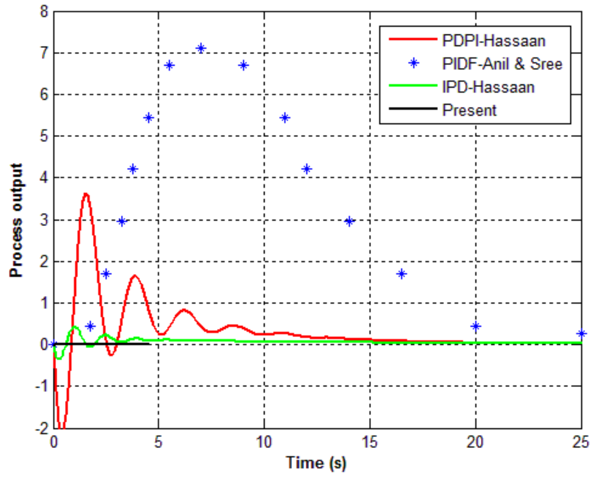

Fig.7 Disturbance time response comparison.

The present work gives outstanding time response compared with the other techniques. The time based specifications are compared in Table 2.

Table 2: Performance comparison.

	c_{max}	T_{cmax} (s)	T_s (s)
Present (PI-PD)	0.026	0.047	0
I-PD [..]	0.431	1.010	15
PD-PI [..]	3.619	1.509	19
PIDF [..]	7.100	7.000	32.5

VII. CONCLUSION

- A PI-PD controller was used for disturbance rejection associated with delayed double integrating processes.
- A process time delay between 0.1 and 2 seconds was covered.
- The controller was tuned using the MATLAB optimization toolbox and five different objective functions were examined.
- The time response of the control system to a unit disturbance input had an oscillating nature for all the objective functions investigated.
- Excellent control system performance based on time response was obtained using the ISTE objective function.
- The effect of process time delay on the control system performance was investigated during disturbance rejection.
- The maximum output time response varied between 0.0018 and 0.0373 for process time delay between 0.1 and 2 s.
- The time at the maximum output time response varied between 0.0281 and 0.17 seconds for the same time delay period.
- The settling time of the time response was zero for the same time delay period.

- Comparing with the research work using I-PD, PD-PI and PIDF controllers, the maximum response for a unit disturbance input of a unit gain and unit time delay double integrating process was 0.0476 compared with 0.431 for I-PD controller, 3.619 for PD-PI controller and 7.1 for PIDF controller.
- The time at the maximum time response was 0.0476 s compared with 1.01 s for I-PD controller, 1.509 s for PD-PI controller and 7 s for PIDF controller.
- The settling time was zero compared with 15 s for I-PD controller, 19 s for PD-PI controller and 32.5 s for PIDF controller.

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