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Controller Tuning for Disturbance Rejection Associated with Delayed Double Integrating Processes, Part V: 2DOF Controller

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Abstract:

The objective of the paper is to investigate the possibility of using a 2DOF controller in disturbance rejection associated with delayed double integrating processes. The effect of time delay of the process in a range between 0.1 and 0.9 seconds is considered. The controller is tuned using MATLAB optimization toolbox with three forms of the objective function in terms of the error between the step time response of the closed-loop control system and the desired zero value. Using the proposed controller with the fractional delayed double integrating process indicates the robustness of the controller in the time delay range used. The 2DOF controller is able to complete with the PID plus first-order lag controller , but it can not compete with other types of controllers such as the I-PD and PD-PI controllers..

***Keywords* — Delayed double integrating process, 2DOF controller, controller tuning, MATLAB optimization toolbox, Control system performance.**

I. INTRODUCTION

In a series of research papers the author investigated five types of feedforward controllers for the purpose of disturbance rejection associated with one of the difficult unstable processes which is the delayed double integrating process. This is the fifth paper of this series exploring the effectiveness of using a two-degree of freedom (2DOF) controller for this purpose and comparing the performance of the control system with other types of controllers in the same series.

Wang (2004) studied the design of robust tracking controller of feed drive for high-speed machining applications. He tested the tracking performance of both a cascade controller and 2DOF tracking controller with discrete time SMC. He concluded that the 2DOF tracking controller outperformed the cascade controller in accuracy and dynamic stiffness [1]. Miklosovic and Gao (2004) introduced a robust 2DOF control design technique extending the concepts of active disturbance rejection control and PID control in new directions. They assigned the transfer functions of the 2DOF controller elements for double integrator process without time delay [2]. Taroco, Mazzini and Ribeiro (2008) studied the tuning of 2DOF PI/PID controller associated with second-order unstable processes. They showed that the set-point time responses were satisfactory and could be independently tuned [3].

Pokar and Prokop (2008) demonstrated the utilization of algebraic controller design in an unconventional ring when controlling integrating processes with time delay. The considered a 2DOF control structure and adopted the dominant pole assignment to tune the controller [4]. Guvenc, Guvenc and Karaman (2010) investigated the use of 2DOF control structure as a robust steering controller for yaw stabilization tasks for driver-assist system. They used steering tasks with and without the controller to see the effect of using the controller to improve vehicle handling quality [5]. Liu and Gao (2010) used a 2DOF control structure allowing for independent regulation of load disturbance rejection from set-point tracking. They have given an illustrative example to show the effectiveness and merits of their proposed method [6]. Huba and Tapak (2011) presented experimental verification of a modified filtered Smith predictor with primary 2DOF P-controller. They showed that the solutions with a second-order disturbance filter were much more sensitive than those with first-order one [7].

Liu and Gao (2011) proposed a modified IMC-based controller designs to deal with step or ramp load disturbance. They developed analytical controller formulae based on 2DOF control structure allowing separate optimization of load disturbance rejection from set-point tracking. They presented illustrative examples to show effectiveness and merits of their proposed method for different cases of load disturbance [8]. Yesil, Guzelkaya and Eksin (2012) proposed an online tuned set-point regulator with a fuzzy mechanism. The control structure exploited the advantages of 1DOF and 2DOF control forms. They used the IMC methodology to design the PI controller incorporated in both control forms [9]. Sutikno, Abdul aziz, Yee and Mamat (2013) developed a 2DOF controller to overcome the weakness of using IMC for disturbance rejection. They proposed a tuning method based on using maximum peak and gain margin of the control system. They evaluated the effectiveness of their tuning method and compared with IMC controller tuning program [10].

Valecha, Narayan and Kumar (2014) presented a design methodology for 2DOF observer based controller for integral processes with dead-time. They used particle swarm optimization to tune the feedback controller and pre-filter designs. They demonstrated the efficiency of their design approach using three design examples [11]. Tang and Li (2014) proposed a compliant 2DOF micro-nanopositioning stage with modified lever displacement amplifiers for the atomic force microscope scanning system. They designed an active disturbance rejection controller including the components of nonlinearity tracking differentiator, extended state observer and nonlinear state error feedback for automatically estimating and suppressing the plant uncertainties [12]. Wul, Wang and Wang (2015) proposed a dynamic modeling of a heavy duty parallel manipulator. They presented a double feedforward control. They concluded that the tracking performance was improved using their proposed method [13].

II. PROCESS

The controlled process is 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 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 [14]:

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

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

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

III. CONTROLLER

The controller used is a feedforward 2FOF controller having the structure shown in Fig.1 [2,3].

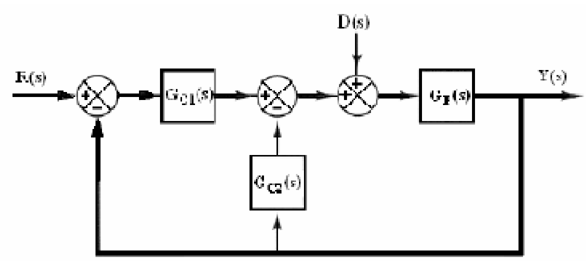

Fig.1 2DOF controller structure [3].

The block diagram of the control system of Fig.1 has two inputs: reference input R(s) and disturbance input D(s). The 2DOF controller has two transfer functions: $G_{c1}(s)$ in the forward path and $G_{c2}(s)$ in the feedback path. According to the work of Miklosovic and Gao, they have the following mathematical expressions for double integrating processes [2]:

$$G_{c1}(s) = K_i / s \qquad (4)$$

And $$G_{c2}(s) = K_{pc} + K_d s \qquad (5)$$

Where K_{pc}, K_i and K_d are the gain parameters of the 2DOF controller.

IV. CONTROL SYTEM TRANSFER FUNCTION

According to the block diagram in Fig.2 for disturbance rejection analysis, the reference input R(s) is set to zero and the closed loop transfer function of the resulting control system , M(s) will be :

$$M(s) = (b_0 s^2+b_1 s) / [a_0 s^3 a_1 s^2+a_2 s + a_3] \quad (6)$$

Where:

$b_0 = -T_d K_p$
$b_1 = K_p$
$a_0 = 1-T_d K_p K_d$
$a_1 = K_p K_d - T_d K_p K_{pc}$
$a_2 = K_p K_{pc} - T_d K_p K_{pc}$
$a_3 = K_p K_i$

V. CONTROLLER TUNING AND SYTEM TIME RESPONSE

The controller has three parameters: K_{pc}, K_i and K_d. The controller parameters are tuned as follows:

- The optimization toolbox of MATLAB is used to assign the other three parameters of the controller (K_{pc} , K_i and K_d) [15].
- The MATLAB command '*fminunc*' is used [15].
- A number of objective functions based on the error between the step time response of the control system for a unit disturbance input and its zero desired value are selected to tune the compensators. They are ITAE [16], ISE and IAE [17].
- The tuning procedure is applied for a specific time delay of the double integrating process in the range $0.1 \le T_d \le 0.9$ s.
- The step response of the closed-loop control system is plotted using the command '*step*' of MATLAB [18].
- The time-based specifications of the control system are extracted using the MATLAB command '*stepinfo*' [18].

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
CONTROLLER TUNING FOR PROCESS UNIT GAIN AND 0.1 s TIME DELAY

Objective Function	K_{pc}	K_i	K_d
ITAE	9.8652	2.3845	9
ISE	9.8652	2.3845	9
IAE	9.8652	2.3845	9

With this controller, changing the objective function did not have any impact on the tuning process of the controller parameters, and hence on the time response of the control system to a unit disturbance input. The time response of the control system for a unit step disturbance input is shown in Figs.2 for time delay of 0.1 s

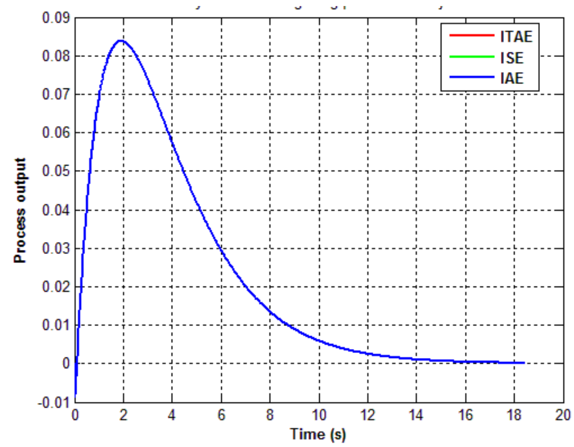

Fig.2 Control system time response for a 0.1 s time delayed double integrating process.

The effect of time delay of the time response of the closed-loop control using ITAE in tuning the 2DOF controller is shown in Fig.3.

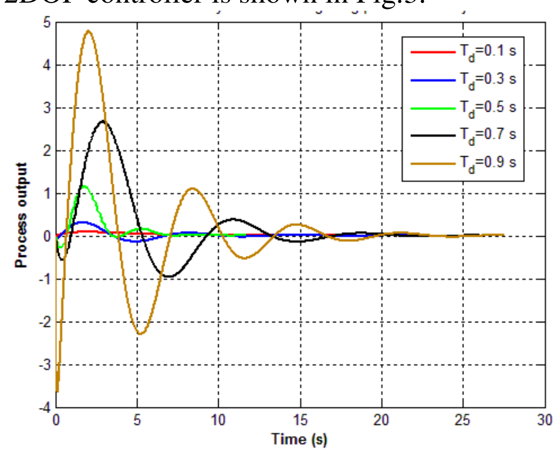

Fig.3 Effect of delay time on system time response.

The effect of the time delay of the double integrating process on some of the time-based specifications of the control system is shown in Fig.4 using the ITAE objective function.

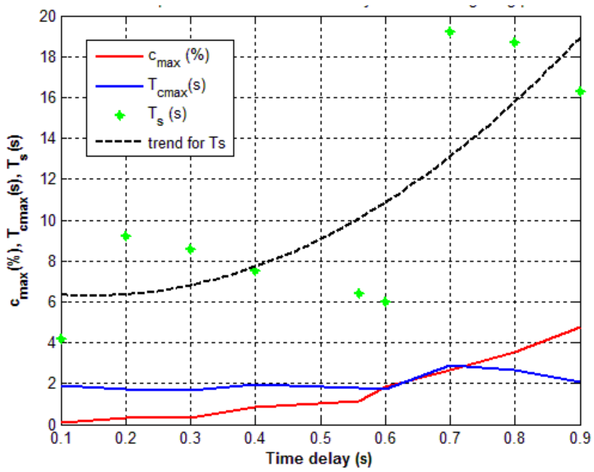

Fig.4 Effect of process time delay on maximum response, time of maximum response and settling time.

The maximum time response due to the unit disturbance input increases as the time delay increases. The time of the maximum response has a mean value of 2.04 s with standard deviation of 0.436 s. The settling time increases as the time delay increases from 0.1 to 0.9 s as clear from its trend.

VI. COMPARISON WITH OTHER RESEARCH WORK

The unit disturbance input time response of the control system for disturbance rejection using the 2DOF controller is compared with the work of Hassaan using I-PD controller [19], PD-PI controller [20] and PID plus first-order lag controller [21] for the same unit gain double integrating process with 0.1 s time delay. The comparison is shown graphically in Fig.5.

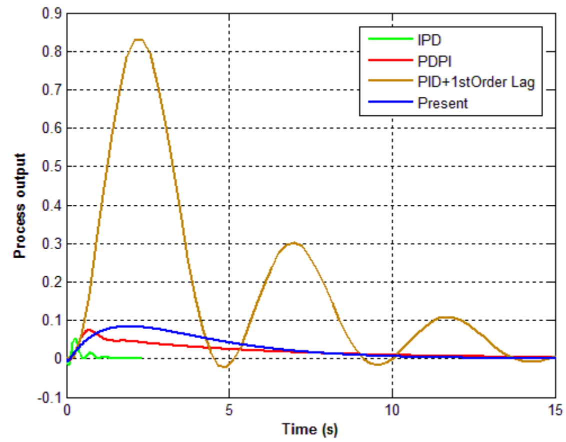

Fig.5 Time response comparison for 0.1 s time delay.

The time based specifications of the four time responses in Fig.5 are compared in Table 2.

TABLE 2
COMPARISON OF CONTROL SYSTEM SPECIFICATIONS

Controller	c_{max}	T_{cmax} (s)	T_s (s)
I-PD	0.0538	0.2721	0.3
PD-PI	0.0735	0.7178	1.2
PID+first order lag	0.8314	2.3327	13.0
Present	0.0838	1.9089	4.2

VII. CONCLUSION

- The dynamic problem of tuning a 2 DOF feedforward controller for use with a fractional delayed double integrating process for the purpose of disturbance rejection was investigated.
- The effect of the process time delay on the tuning results and the time response of the control system was investigated.
- Thee objective function forms were applied to tune the compensator.
- It has been shown that choosing a suitable objective function had no effect on the tuning operation of the 2DOF controller.
- The examined 2DOF controller could compete with the PID plus first-order lag controller, but could not compete with the other controller types such as the I-PD and PD-PI controllers.
- The time delay had a remarkable effect of the disturbance input time response of the control system.
- The feedforward 2DOF controller was robust against the change in the fractional process time delay in the range between 0.1 and 0.9 seconds in terms of system stability and performance.

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