Disturbance Rejection with Highly Oscillating Second-order-like Process, Part V: 2DOF PID-PI Controller

Galal Ali Hassaan

***Abstract*— The use of a 2DOF PID-PI controller for disturbance rejection of one of the difficult processes having highly oscillating characteristic with maximum overshoot of above 85 % is investigated. The proposed controller has five parameters reduced to three to be adjusted to produce successful disturbance rejection. The controller is tuned using MATLAB control and optimization toolboxes through using five error-based objective functions. To examine the effectiveness of the proposed compensator, it is compared with three controllers investigated before to control the same process. The proposed controller can compete well with the PD-PI and PI-PD controllers. It can generate time response to unit step disturbance input with maximum value as low as 0.97 x 10^{-4}.**

***Index Terms*— Disturbance rejection, 2DOF PID-PI controller, Controller tuning, second-order-like process, control system performance.**

I. INTRODUCTION

This is the fifth research paper in a series of papers aiming at investigating non-conventional controllers for disturbance rejection associated with one of the difficult process to control which is a second order-like process having 85.4 % maximum overshoot.

Zhong and Rico (2002) used a disturbance observer-based 2DOF controller to control integral processes with dead time. They tuned the controller according to compromise between disturbance response and robustness [1]. Miklosovic and Gao (2004) introduced a robust 2DOF control design technique extending the concepts of active disturbance rejection and PID control in new directions. They tuned one or two parameters giving their technique its practicability. They verified their approach using an actual motion control platform [2]. Shamsuzzoha, Jeon and Lee (2007) proposed the design of a PID controller cascaded with first order filter for second order unstable time delayed processes. They compared their work with published tuning methods showing the superiority of their proposed method [3].

Alfaro, Vilanova and Arrieta (2008) presented a design approach for 2DOF PID controllers for smooth control. They provided tuning the 2DOF PI and 2DOF PID controllers. There was no need for identification experiment for the tuning of the inner controller [4]. Toroco, Mazzini and Ribeiro (2008) presented a simple method for 2DOF controllers for second order unstable processes. They obtained explicit expressions of PID tuning parameters using specifications of the desired closed-loop transfer function for the disturbance response. They showed that their proposed method provided good performance in terms of disturbance rejection, set-point tracking and robustness [5]. Chou and Hsinchu (2009) developed robust 2DOF current and torque control schemes for a permanent magnet synchronous motor with satellite reaction wheel load.. They augmented the traditional 2DOF controller with an internal model feedback resonant controller or a robust tracking error cancellation controller. They evaluates experimentally the effectiveness of the proposed control [6].

Vrancic and Huba (2011) presented a tuning method based on characteristic areas and magnetic optimum criterion for some unstable processes. They used a 2DOF PI controller tuned depending on desired tracking or disturbance rejection performance. They tested their proposed method using five linear process models [7]. Bagheri and Nemati (2011) proposed a tuning procedure for PI controllers in 2DOF structure. They demonstrated the effectiveness and validity of their proposed method for a wide variety of processes [8]. Przyhyla et. al. (2012) presented a practical verification of an active disturbance rejection method. They conducted experiments on a 2DOF planar manipulator with only partial knowledge about the plant mathematical model. They reported better results compared with that using two decentralized classic PID controllers [9].

Sutikno, Abdel Aziz, Yee and Mamat (2013) developed a 2DOF-IMC controller to overcome the weakness of using IMC in disturbance rejection problems. They tested their tuning method using first order plus dead time and higher order processes [10].

Chitsanga and Kaitawanidvilai (2014) presented a method for a 2DOF H infinity control of a DC motor. They used genetic algorithms to achieve the specified structure robust control design. They verified the effectiveness, good performance and robustness of their proposed technique [11]. Kumar and Patel (2015) presented a design approach for 2DOF PID controllers for second-order processes with time delay. Their controller has given better results compared to PID controller used with the same process [12]. Hassaan (2015) investigated using a 2DOF controller in disturbance rejection associated with delayed double integrating processes. He tuned the controller using MATAB optimization toolbox and indicated the robustness of the controller in the covered process delay time range. The 2DOF controller was able to compete with PID plus first order lag controller [13].

II. PROCESS

The process dynamics can be represented by an equivalent second-order-like process model having the transfer function, $G_p(s)$:

$$G_p(s) = \omega_n^2 / (s^2 + 2\zeta\omega_n s + \omega_n^2) \quad (1)$$

Where:

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ω_n = process natural frequency = 10 rad/s
ζ = process damping ratio = 0.05

This process has a maximum percentage overshoot of 85.4 %.

III. CONTROLLER

The controller is a 2DOF PID-PI one having the structure shown in Fig.1 [5].

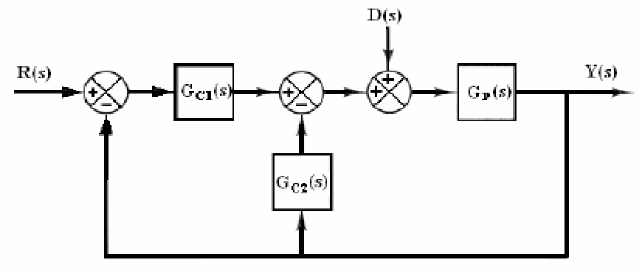

Fig.1 Control system block diagram with 2DOF controller [5].

The 2DOF controller has two elements:
- One element in the forward path of the system block diagram, Gc1(s).
- Another element in the feedback path of the control system, Gc2(s).

The process has a transfer function Gp(s).

The feedforward path element of the controlled is a conventional PID controller having a transfer function, $G_{c1}(s)$ given by:

$$G_{c1}(s) = K_{pc} + Ki/s + K_d s \tag{2}$$

Where: K_{pc} = proportional gain.
K_i = integral gain.

The feedback element is a PI controller having a transfer function Gc2(s) given by:

$$G_{c2}(s) = K_{pc} + Ki/s \tag{3}$$

It has a proportional gain K_{pc} and an integral gain Ki having the same values as in the PID controller element in Eq.2. It is possible to set them at different levels than those in Eq.2. However, by investigating the transfer function of the closed loop control system with disturbance input I found that there is no meaning in this application to use different levels for K_{pc} and K_i in both controller elements.

IV. CLOSED-LOOP TRANSFER FUNCTION

To investigate disturbance rejection, the reference input R(s) in Fig.1 is omitted and the disturbance input D(s) is considered as the control system input and C(s) , process output, is its output. In this context, the closed loop transfer function of the control system using the block diagram in Fig.1 and Eqs.1, 2 and 3 becomes:

$$C(s) / D(s) = b_0 s / (s^3 + c_0 s^2 + c_1 s + c_2) \tag{4}$$

Where:

$b_0 = \omega_n^2$
$c_0 = 2\zeta\omega_n + K_d\,\omega_n^2$
$c_1 = \omega_n^2(1 + 2K_{pc})$
$c_2 = 2K_i\,\omega_n^2$

V. CONTROLLER TUNING

The controller tuning process provides efficient rejection for the disturbance associated with the highly oscillating second-order process. The procedure used to tune the 2DOF PID-PI controller is as follows:

1. The controller has three parameters to be adjusted: K_{pc}, K_i and K_d.
2. The controller is tuned using specific objective functions based on the error between the time response of the control system to a unit step disturbance input and the desired steady-state response (which is zero in the case of disturbance rejection).
3. The MATLAB control toolbox is used to provide the time response of the control system using the command '*step*' [14].
4. Five error-based objective functions are used to optimize the performance of the control system: ITAE, ISE, IAE, ITSE and ISTSE [15] – [17].
5. The MATLAB optimization toolbox is used to minimize each objective function and tune the compensator parameters a_1 and a_2 [18].
6. A sample of the tuning procedure results using the five objective functions is given in Table 1.

Table 1: Controller tuning results.

Function	ITAE	ISE	IAE	ITSE	ISTSE
K_{pc}	10.9816	10.0857	10.1082	1102.08	395.53
K_i	0.1	0.1	0.1	0.1	0.1
K_d	0.2793	0.2886	0.2889	5.096	0.411
c_{max}	0.05869	0.0622	0.0621	0.0005	0.0023
T_{cmax} (ms)	65.9	68.7	68.6	7.9	11.1
T_s (ms)	90	102	102	0	0

7. The best objective function suitable for the disturbance rejection associated with the second order highly oscillating process using the 2DOF PID-PI controller is the ITSE one. It provides very small time response with very small time of maximum response and settling time.
8. The time response of the control system to a unit disturbance input using the five objective functions is shown in Fig.2.

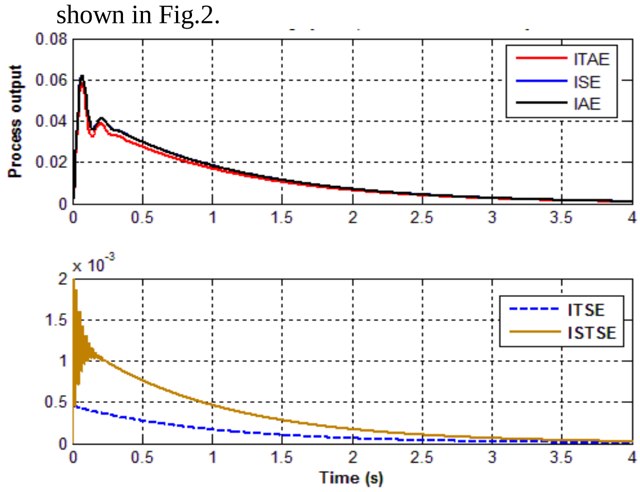

Fig.2 Unit step disturbance input time response using 5 objective functions.

9. The effect of the controller proportional gain K_c on the dynamics of the control system for disturbance rejection associated with the highly oscillating second order process is shown in Fig.3 for K_c in the range from 1000 to 5000.

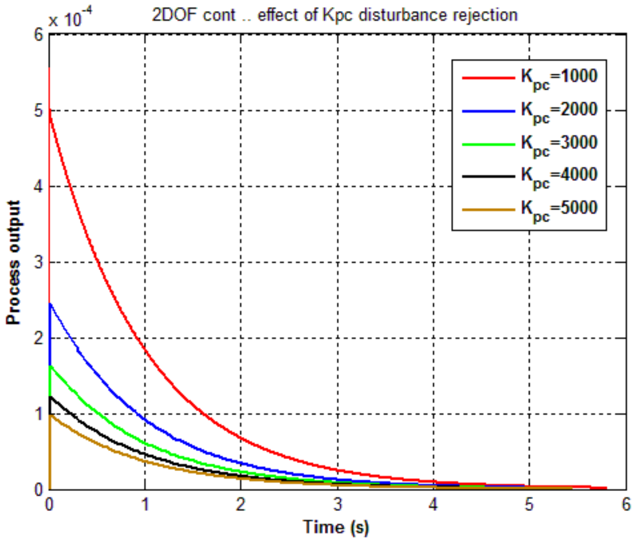

Fig.3 Effect of K_{pc} on the control system time response.

10. Increasing the proportional gain of the controller is in favor of the disturbance rejection process. However, the rate of decrease of the time response values decreases as the proportional gain increases.
11. The effect of the proportional gain K_{pc} on some of the performance measures of the control system response is shown in Fig.4 for the settling time T_s and Fig.5 for the steady-state error e_{ss}.

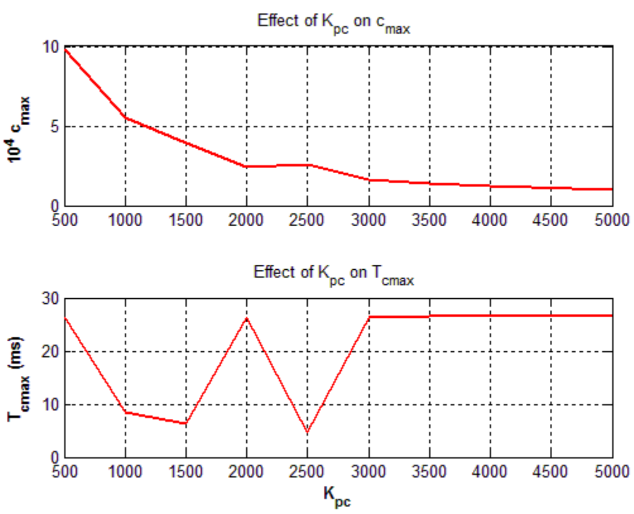

Fig.4 Effect of K_{pc} on the maximum time response and its time.

12. The maximum time response continue decreasing as the proportional gain increases but with decreased rate towards the end of the gain range.
13. The time of maximum time response settles at 26.5 ms as the proportional gain increases than 3000.

VI. COMPARISON WITH OTHER CONTROLLERS

To investigate the effectiveness of the proposed controller, it is compared with the results of some other controllers used by the author in the same series for disturbance rejection of the highly oscillating process. The present controller is compared with the PD-PI controller [19] , PI-PD controller [20] and IPD controller [21]. The comparison is presented in Fig.5 for the same process and the same unit step disturbance input.

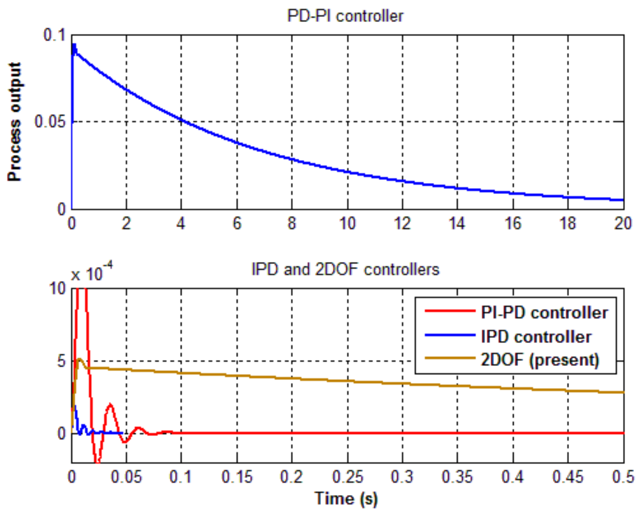

Fig.5 Comparison with PD-PI, IPD and PI-PD controllers.

VII. CONCLUSION

- A 2DOF PID-PI controller was introduced in this work for disturbance rejection associated with a highly oscillating second-order-like process.
- The controller had five parameters reduced to three parameters, to be tuned for optimal performance of the control system during disturbance rejection.
- The controller parameters were tuned using MATLAB control and optimization toolboxes.
- Five objective functions were used in the controller tuning process to assign the best of them suitable for the process under control.
- It has been shown that the ITSE objective function was the best in tuning the controller parameters.
- Using the proposed controller, it was possible to go down with the maximum time response value to as low as $0.97\text{x}10^{-4}$.
- It was possible to go down with the time of maximum time response to only 26.5 ms.
- It was possible to go down with the settling time to zero at a controller proportional gain > 500.
- The performance of the control system using the proposed controller was compared with that using other controllers investigated by the author in same series of research papers.
- The 2DOF PID-PI controller could compete well with the PD-PI and PI-PD controllers, but it could not compete with the IPD controller.

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