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TUNING OF A PID CONTROLLER FOR DISTURBANCE REJECTION ASSOCIATED WITH HIGHLY OSCILLATING SECOND ORDER PROCESS

Galal Ali Hassaan*

Emeritus Professor, Department of Mechanical Design and Production, Faculty of Engineering, Cairo University, Egypt.

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***Corresponding Author**
Prof. Dr. Galal Ali Hassaan
Emeritus Professor, Department of Mechanical Design and Production, Faculty of Engineering, Cairo University, Egypt.

ABSTRACT

Efforts is made by the author between 2014 and 2018 to introduce a second generation of PID controllers. The application of a conventional PID controller to control the disturbance rejection associated with a highly oscillating second order process. For purpose of enhancing the use of some controllers from the second generation as a replacement for old PID controllers, the paper presents the I-PD, PD-PI, PI-PD and 2DOF PID-PI controllers for the purpose of disturbance rejection. Step time response characteristics is compared for the PID against the other four controllers and the best controllers are outlined.

KEYWORDS: Conventional PID controller, highly oscillating second order process, disturbance rejection, PID controller tuning for disturbance rejection, comparison with other controllers, second generation of PID controllers.

INTRODUCTION

Most industrial processes and other plants such as aerospace vehicles suffer from disturbance due to electrical noise and external force disturbance. One of the objectives of controller selection and design is to minimise the effect of such disturbances on the process output. The objective of this paper is to investigate the tuning of the conventional PID controller to minimize the process response due to the disturbance input and to compare the use of other controllers from what is called the second generation of PID controllers.

Ogawa, 1997 presented a tuning method for PID controller for robust load disturbance rejection. He applied his tuning method for first-order delay with dead time and an integrating with dead time processes. He compared the performance of PI and PID controllers when used to control the two processes.[1] Vrancic and Lumbar, 2004 in their report about the improvement of PID controller disturbance rejection by means of magnitude optimization (MO). They applied their proposed tuning technique to a number of processes including a firth order process, third order process. They compared the disturbance properties using MO and DRMO methods for 63 process models.[2] Kim and Cho, 2005 proposed a design approach for PID controller against external disturbance in motor control system using bactyrial foraging optimal algorithm. They illustrated the disturbance rejection conditions based on the H∞ and compared the response performance based on the bacrerial foraging based optimization.[3]

Zlosnikas and Baskys, 2008 suggested a PID controller with enhanced load disturbance rejection employing different values of controller parameters during set-point change and load disturbance responses of the control system.[4] Veronesi and Visjoli, 2015 proposed an algorithm for the load disturbance rejection performance assessment of a PID controller. Their approach covered also the retuning of the controller performance in case the obtained response is not satisfactory.[5] Patil, Malwatkar and Kalcarni, 2012 described a tuning procedure for ideal PID controller in series with a first-order low-pass filter based on the direct synthesis approach. Their proposed design provided better disturbance rejection than the standard direct synthesis. In one of the examples, the IAE error function was reduced by up to 85 % using their tuning technique.[6] Gamal, Ouda, El-Halwagy and El-Nashar, 2015, presented an approach for an advanced fast disturbance rejection based on using PI controller for a benchmark plant model description. Their design was based on a balance between response time (performance) and stability margins (robustness). They concluded about the use of their procedure for both tracking performance and disturbance rejection.[7] Cvejn and Vrancic, a way to remove the problem of slow disturbance rejection responses when exogenous disturbance affects the process indirectly. They proposed adding two first-order filters into the control loop without modifying the controller parameters.[8] Sarif, Umar and Rao, 2020 presented a technique for PID controller cascaded with an enhanced filter arranged based on an IMC fine-tuning method for disturbance rejection. The optimal technique used provided acceptable response for the proposed models using error criteria of IAE, ISE and ITAE.[9] Vrancic and Huba, 2021 presented an approach in which the PID controller parameters were optimized for reference tracking. The performance of disturbance rejection was increased by introducing a disturbance estimator through the addition of two simple blocks to the PID controller. The proposed technique was applied on several process models showing good tracking and disturbance rejection performance.[10]

The Controlled Process

The controlled process is a highly oscillating second order process having:

- Natural frequency of 10 rad/s.
- Damping ratio of 0.05 (the low value reflects the high oscillation characteristic of the process).
- Maximum percentage overshoot of 85 %.
- Settling time of 8 s.

The high oscillations of the second order process represent a real challenge in controlling the process either for input tracking or for disturbance rejection. The process has 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: ω_n = process natural frequency rad/s

ζ = process damping ratio

Block Diagram of the Control System

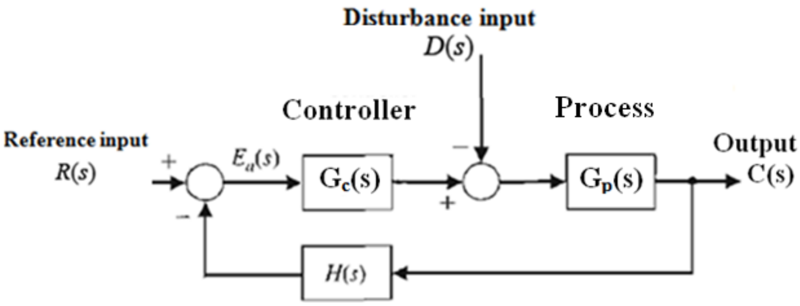

Fig. 1: Control system with reference and disturbance inputs.[11]

A control system incorporating a conventional PID controller and the process with reference input R(s) and a disturbance input D(s) is shown in Fig.1.[11]

PID Controller for Disturbance Rejection

A feedforward parallel PID controller has a transfer function, $G_c(s)$ given by[12]:

$$G_c(s) = K_{pc} + (K_i/s) + K_d s \quad (2)$$

Where: K_{pc} = controller proportional gain

K_i = controller integral gain

K_d = controller derivative gain

Using the block diagram in Fig.1, the controller transfer function in Eq.2 and the process transfer function in Eq.1 with zero reference input, the transfer function of the control system with D(s) as an input, M(s) is:

$$M(s) = C(s)/D(s) = b_0 s / (a_0 s^3 + a_1 s^2 + a_2 s + a_3) \quad (3)$$

Where: $b0 = \omega_n^2$

$a_0 = 1, a_1 = 2\zeta\omega_n + K_d\, \omega_n^2$

$a_2 = (1 + K_{pc})\, \omega_n^2,\ a_3 = K_i\, \omega_n^2$

With disturbance input of the control system, the error function between the output variable time response and the steady state response(supposed to be zero) will be the time response of the control system, c(t). The MATLAB optimization command '*fminunc*'[13] is used to tune the PID controller using the error based objective function ITAE.[14] The tuning results are:

$$K_{pc} = 4.4988,\ K_i = 3.0126,\ K_d = 2.2520 \quad (4)$$

The unit step time response of the control system using the transfer function in Eq.3, process parameters in Eq.1 and tuned PID controller parameters in Eq.4 is shown in Fig.2. The characteristics of the step time response for disturbance rejection using the PID controller is evaluated two parameters:

- The maximum time response, c_{max}.
- The settling time, T_s using a 0.02 band drawn in Fig.2 as a dashed black line.

Using the '*max*' command of MATLAB[15] and Fig.2, the disturbance rejection characteristics using the PID controller are:

$$c_{max} = 0.1366,\ T_s = 4s \quad (5)$$

Comparison with Controllers from the PID Second Generation

The author introduced during the period 2014-2018 a large number of PID-based controllers aiming at providing good dynamic solution for the kick associated with PID controller for reference tracking.[16] Four controllers from the series of the second generation of PID controllers are applied here to reject the disturbance associated with the highly oscillating second order process as follows:

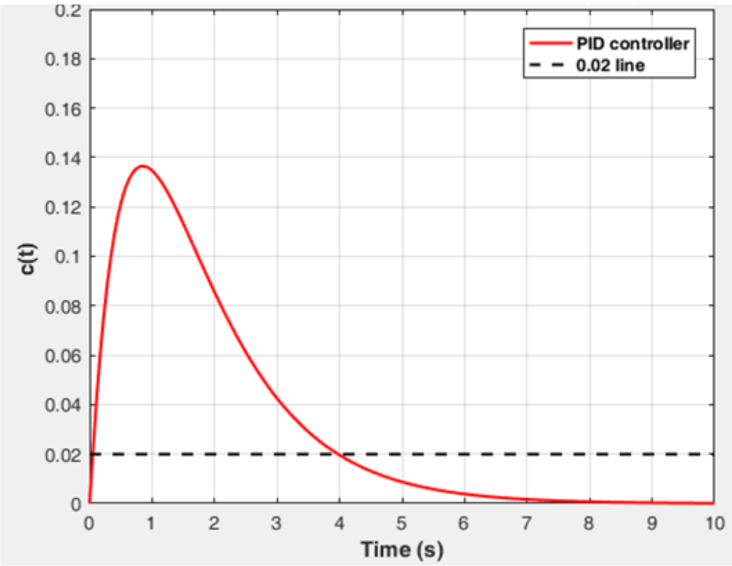

Fig. 2: Disturbance rejection using a PID controller.

- I-PD controller used by the author in 2014 for reference input tracking associated with the highly oscillating process.[17]
- PD-PI controller used by the author in 2014 for reference input tracking associated with the highly oscillating process.[18]
- PI-PD controller used by the author in 2014 for reference input tracking associated with the highly oscillating process.[19]
- 2DOF PID-PI controller used by the author in 2018 for reference input tracking associated with second-order-like processes.[20]

I-PD Controller for Disturbance Rejection

A block diagram for a control system used for disturbance rejection using an I-PD controller is shown in Fig.3. Here of course the reference input will be set to zero in order that the control system can provide its response to the disturbance associated with the process. The controller has three parameters:

- Integral time constant, T_i.
- Proportional gain, K_{pc}.
- Derivative time constant, T_d.

The transfer function C(s)/D(s) with R(s) = 0 was derived and used to tune the I-PD controller when used with the second order process having 10 rad/s natural frequency and 0.05 damping ratio.[21] The tuned controller parameters using an ISTSE objective function and the MATLAB command '*fminunc*' are[21]:

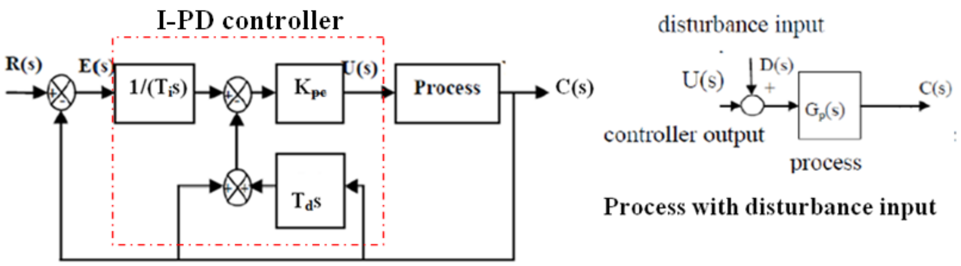

Fig. 3: Control system for disturbance rejection using I-PD controller.[21]

$$T_i = 0.0305s,\ K_{pc} = 233.83;\ T_d = 0.0042s \qquad (6)$$

A unit step disturbance input results in a step response of the control system using an I-PD controller with the tuned parameters in Eq.6 shown in Fig.4 with comparison with the disturbance rejection using the conventional PID controller.

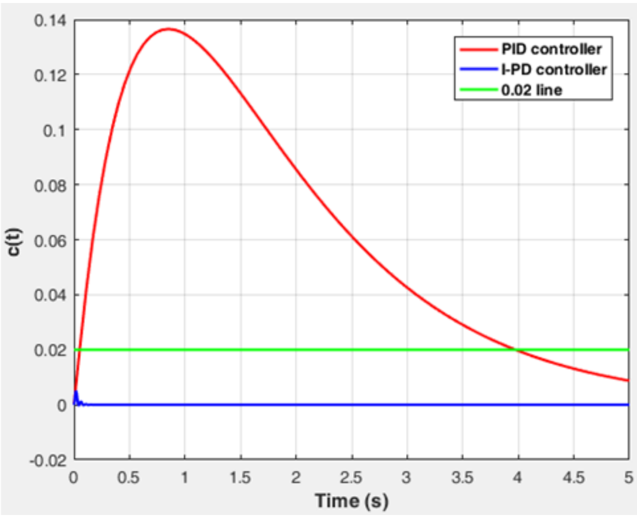

Fig. 4: Disturbance rejection using an I-PD controller.

The effectiveness of using the I-PD controller for disturbance rejection is measured through using the following functional parameters:

- The maximum time response, c_{max} is 0.005 compared with 0.1366 when a PID controller is used.
- The settling time, T_s is zero compared with 4 s when a PID controller is used.

PD-PI Controller for Disturbance Rejection

A block diagram for a control system used for disturbance rejection using a PD-PI controller is shown in Fig.5.[22] The controller has three parameters:

- Proportional gain, K_{pc}.
- Derivative gain, K_d.

- Integral gain, K_i.

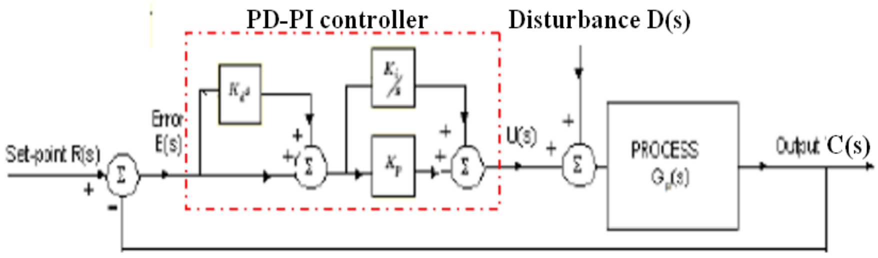

Fig.5: Control system for disturbance rejection using PD-PI controller.[22]

The transfer function C(s)/D(s) with R(s) = 0 was derived and used to tune the I-PD controller when used with the second order process having 10 rad/s natural frequency and 0.05 damping ratio.[23] The tuned controller parameters using an ISTSE objective function and the MATLAB command '*fminunc*' are[23]:

$$K_d = 0.0457, K_{pc} = 24.697; K_i = 1.6176 \quad (7)$$

A unit step disturbance input results in a step response of the control system using an PD-PI controller with the tuned parameters in Eq.7 shown in Fig.6 with comparison with the disturbance rejection using the conventional PID controller.

The effectiveness of using the PD-PI controller for disturbance rejection is measured through using the following functional parameters:

- The maximum time response, c_{max} is 0.047 compared with 0.1366 when a PID controller is used.
- The settling time, T_s is 10s compared with 4 s when a PID controller is used.

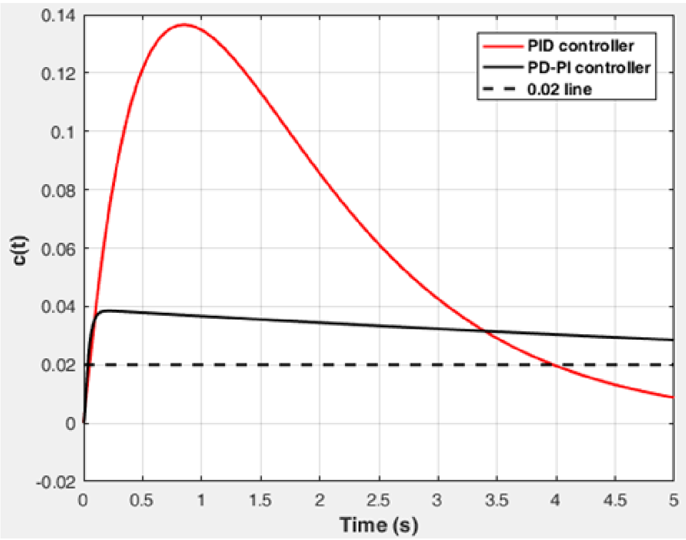

Fig. 6: Disturbance rejection using a PD-PI controller.

PI-PD Controller for Disturbance Rejection

A block diagram for a control system used for disturbance rejection using a PI-PD controller is shown in Fig.7.[24] The controller has two parts: A feedforward part which is a PI sub-controller with K_{pc} and T_i parameters and a feedback part which is a PD sub-controller with K_f and T_d parameters in a closed loop with the process. It PI-PD controller has the parameters:

- Proportional gain of feedforward PI sub-controller, K_{pc}.
- Time constant of feedforward PI sub-controller, T_i.
- Proportional gain of feedback PD sub-controller, K_f.
- Time constant of feedback PD sub-controller, T_d.

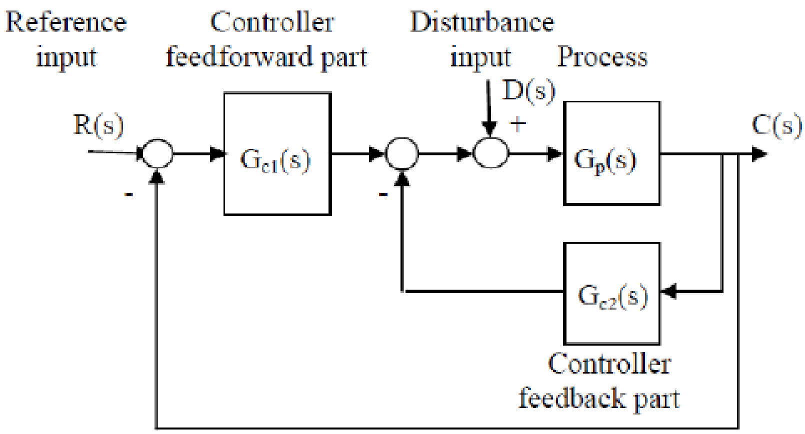

Fig.7: Control system for disturbance rejection using a PI-PD controller.[24]

The transfer function C(s)/D(s) with R(s) = 0 was derived and used to tune the PI-PD controller when used with the second order process having 10 rad/s natural frequency and 0.05 damping ratio.[24] The tuned controller parameters using an ITAE objective function and the MATLAB command '*fminunc*' are[24]:

$K_{pc} = 10.0119$, $T_i = 0.074$ s, $K_f = 4.9902$, $T_d = 0.0535$ s (7)

A unit step disturbance input results in a step response of the control system using an PD-PI controller with the tuned parameters in Eq.8 shown in Fig.8 with comparison with the disturbance rejection using the conventional PID controller.

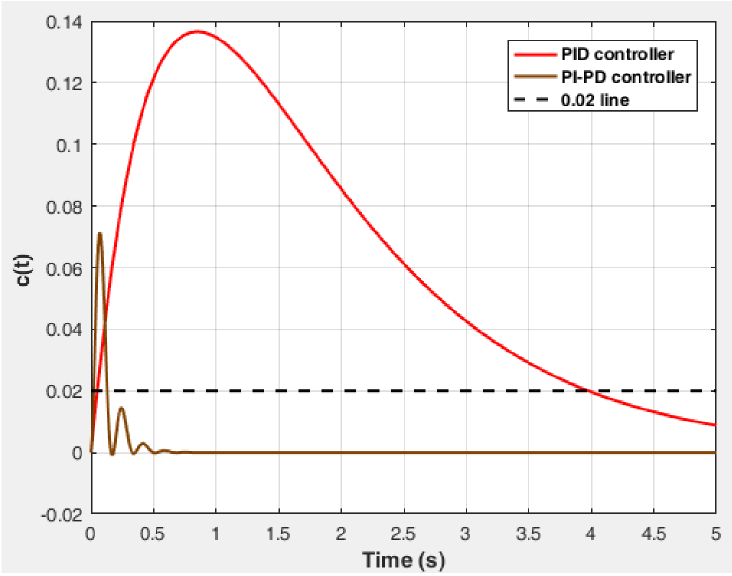

Fig. 8: Disturbance rejection using a PI-PD controller.

The effectiveness of using the PI-PD controller for disturbance rejection is measured through using the following functional parameters:

- The maximum time response, c_{max} is 0.0712 compared with 0.1366 when a PID controller is used.
- The settling time, T_s is 0.18s compared with 4 s when a PID controller is used.

2DOF PID-PI Controller for Disturbance Rejection

A block diagram for a control system used for disturbance rejection using a two degree of freedom 2DOF PID-PI controller is shown in Fig.9.[25] The PID sub-controller has a transfer function $G_{c1}(s)$ given by Eq.2 and the PI sub-controller has a transfer function $G_{c2}(s)$ given also by Eq.2 with K_d = 0. Therefore, the controller has three parameters:

- Proportional gain, K_{pc}.
- Derivative gain, K_d.
- Integral gain, K_i.

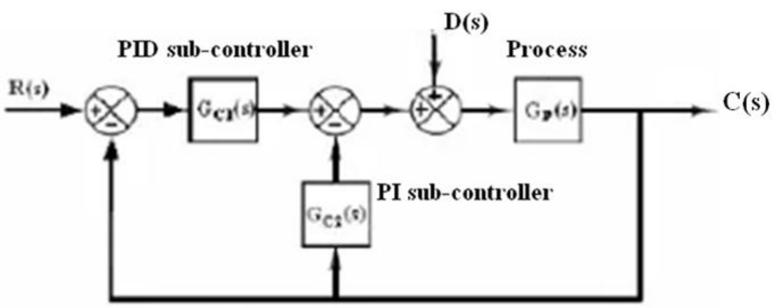

Fig.9 Control system for disturbance rejection using a 2DOF PID-PI controller [25].

The transfer function C(s)/D(s) with R(s) = 0 was derived and used to tune the 2DOF PID-PI controller when used with the second order process having 10 rad/s natural frequency and 0.05 damping ratio. The author used an ISE objective function without any functional constraints in a MATLAB script written specially for this tuning problem. The tuned 2DOF PID-PI controller parameters are:

$$K_{pc} = 17.4890,\ K_i = 48.0938;\ K_d = 50.2406 \qquad (8)$$

A unit step disturbance input results in a step response of the control system using a 2DOF PID-PI controller with the tuned parameters in Eq.8 is shown in Fig.10 with comparison with the disturbance rejection using the conventional PID controller.

The effectiveness of using the 2DOF PID-PI controller for disturbance rejection is measured through using the following functional parameters:

- The maximum time response, c_{max} is 0.009 compared with 0.1366 when a PID controller is used.
- The settling time, T_s is zero compared with 4 s when a PID controller is used.

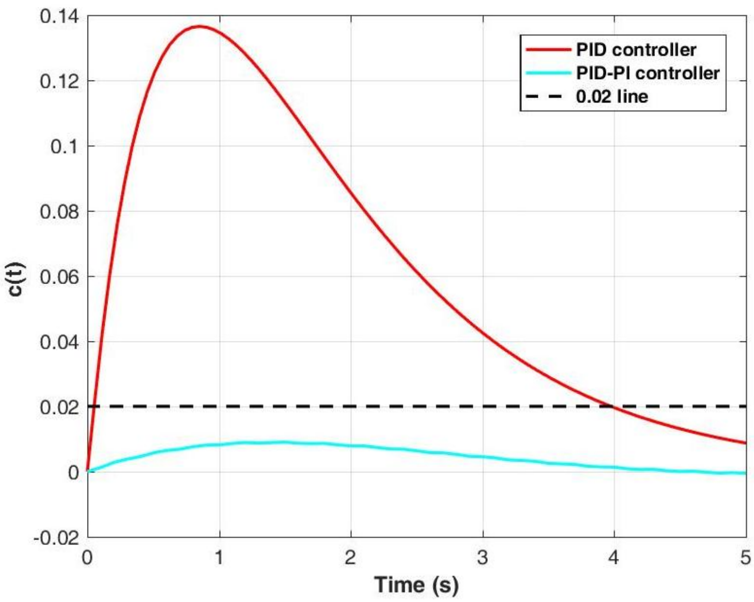

Fig. 10: Disturbance rejection using a 2DOF PID-PI controller.

Comparison of Disturbance Rejection using Five PID-based Controllers

The analysis presented in the previous sections was gathered in one comparison disturbance time response graph as follows:

- One conventional PID controller.
- Four controllers from the second generation of PID controllers.

The unit step response of the control system representing the disturbance rejection of the control system is shown in Fig.11 for PID, I-PD, PD-PI, PI-PD and 2FOF PID-PI controllers.

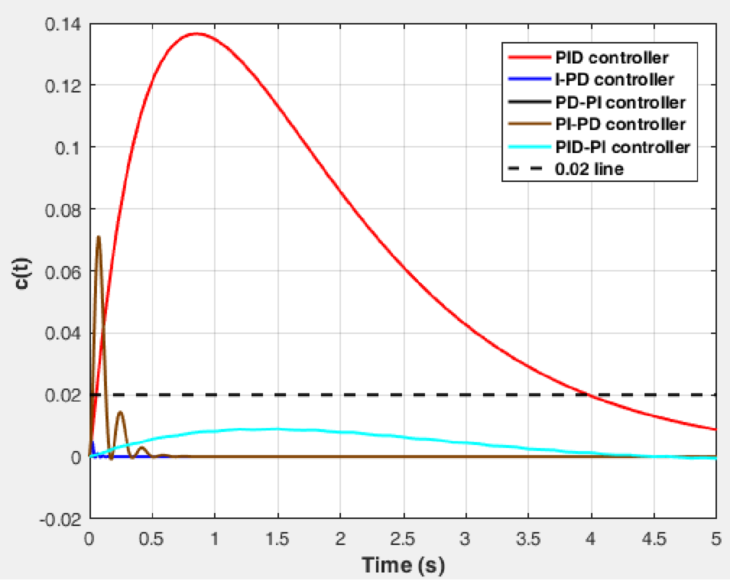

Fig. 11: Disturbance rejection using five controllers.

The characteristics of the disturbance rejection associated with the highly oscillating process using the five controllers presented in this paper are collected in Table 1.

Table 1: Disturbance rejection characteristics associated with s highly oscillating second order process.

Controller	PID	I-PD	PD-PI	PI-PD	2DOF PID-PI
Number of Parameters	3	3	3	4	3
Error Criterion	ITAE	ISTSE	ISTSE	ITAE	ISE
c_{max}	0.1366	0.005	0.047	0.0712	0.009
T_s (s)	4	0	10	0.18	0
Condition	worst	best	-	-	-
Sequence of Best Controllers	5	1	4	3	2

CONCLUSION

- The paper presented the use of the conventional PID controller in the disturbance rejection associated with a highly oscillating second order process.
- The process considered in this study had 10 rad/s natural frequency and 0.05 damping ratio.
- The PID controller was tuned using the MATLAB toolbox and the ITAE error criterion without any functional constraints.

- The tuned PID controller could provide a disturbance rejection step response having 0.1366 maximum time response (c_{max}) and 4 s settling time.
- The paper presented four PID-based controllers from the PID second generation for investigation for possible replacement of the conventional PID controller for purpose of disturbance rejection.
- The first controller from the PID second generation was the I-PD controller which provided disturbance rejection with maximum disturbance step time response of only 0.005 and zero settling time.
- The second controller from the PID second generation was the PD-PI controller which provided disturbance rejection with maximum disturbance step time response of 0.047 and a settling time of 10 s.
- The third controller from the PID second generation was the PI-PD controller which provided disturbance rejection with maximum disturbance step time response of 0.071 and a settling time of 0.18 s.
- The fourth controller from the PID second generation was the 2DOF PID-PI controller which provided disturbance rejection with maximum disturbance step time response of only 0.009 and zero settling time.
- The I-PD controller from the second generation of PID controllers was the best among the five studied controllers in the rejection of the disturbance associated with the considered highly oscillating second order process.
- The conventional PID controller qas the worst among the studied group of controllers.

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