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PD-I CONTROLLER TUNING AND ROBUSTNESS WHEN USED TO CONTROL A THIRD ORDER PROCESS

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ABSTRACT

Processes with high oscillations are not desirable in modern industrial applications. Tuning of controller parameters overcomes this problem. PD-I controller is one of PID controllers within the second generation family. The paper studies the tuning of the PD-I controller to contribute in solving the problem of controlling a highly oscillated third order process. The minimization of error performance indices such as: ITAE, ISE, IAE, ITSE, and ISTSE of the closed loop control system is investigated for the purpose of controller tuning through using the MATLAB optimization toolbox. Some of the control system time based characteristics are used to judge the performance of the control system specifically maximum percentage overshoot and settling time. The proposed tuning technique results are compared with a tuning technique based on the minimum ITAE standard form. The robustness of the PD-I controller is investigated when it is used to control a highly oscillated third order process under process parameters uncertainty within a range of within ± 20 % of its nominal values.

KEYWORDS: PD-I Controller, Controller tuning, Robustness, process uncertainty.

INTRODUCTION

PD-I controllers are a set of PID controllers belonging to the second generation of PID controllers investigated by Prof. Galal Hassaan during the period 2014 to 2018 and applied to some processes having bad dynamics. Here the PD-I controller is applied to a third order process of high oscillations for purpose of tuning the controlling and examining its robustness against the change of the third order process parameters.

Zeid (2009) presented a unified multi-rate biomimetic gaze controller integrating VOR mechanisms with tracking for a robotic head with two cameras. The internal brain circuits controlling eye movements were found to operate with neural delays much smaller than delays in visual processing pathways. They added slip and memory PDI control in the visual feedback to overcome inherent delays in the visual system, increase the tracking response bandwidth and improves steady state tracking gain.[1] Jianqiang (2014) designed a double loop hybrid controller and double variable neural network PDI controller to increase the control precision of a double pneumatic cylinder collaborative loading system and improve its robustness. He found that the neutral network control is strongly adaptive to the unknown, uncertain and non-linear features of the controlled objects, overcome unfavorable influences of the non-linear factors on the system, and improve the control quality.[2] Torres, Oliveira, Rabelo, Sena and Mimoso (2015) introduced a guide for multi rotor implementation involving the tuning of PID controllers. Their study was based on the experience they gained from the assembly of two multi rotors and PDI controller design.[3]

Nogueira, Hugo de Albuquerque and Tavares (2018) compared between using different configurations of controllers digital (P, PD, PI and PDI) controllers to control a brain computer interface (BCI) with Neuro-bio-feedback using SSVEP.[4] Hassaan (2018) investigated the tuning of a novel PD-I controller used with underdamped second order process using the MATLAB control and optimization toolbox. The PD-I controller competed with the PID in overcoming the kick characteristics.[5] Cooper and Heidlauf (2018) compared PID and PDI Controllers against RLS adaptive control and ELS adaptive control. They found that all cases using a PID controller outperformed the cases using the modified PD-I controller.[6]

Ahmed, Mashor and Mahdi (2019) designed a fuzzy PD + I controller for non linear structure. The fuzzy PD-I controller was able to optimize and control the Nano-satellite attitude with accepted performance. They illustrated the effectiveness of the proposed scheme using MATLAB/ SIMULINK programs.[7] Chhabra, Mohan, Rani Sing (2019) designed a fractional order fuzzy FOFPD + I to control a nonlinear robotic manipulator. The generic algorithm had been used to provide the optimum parameters of FOFPD + I, FPD I and PID controllers. The designed PDIF controller was validated experimentally on DC motor. The PDIF was superior than the conventional PID controller.[8]

Smeresky, Rizzo and Sands (2020) investigated different models for the control of rigid body motion mechanics. They compared the PD-I controller with a deterministic artificial intelligence composed of optimal self-awareness statements together with a novel, optimal learning algorithm as ideal nonlinear feed forward and feedback. A newly demonstrated analytically optimal learning yielded the highest accuracy with the lowest execution time.[9] Hassaan (2020) investigated a novel PDIF to control a second order process of 10 rad/s natural frequency and 0.1 damping ratio. The proposed technique showed that the PDIF controller was capable of eliminating the kick associated with PID controller and enhancing the speed of the time response of the control system.[10]

Third Order Process

An industrial process is a set of components organized to perform a specific function. These processes may be mechanical, chemical, electrical, electromechanical….etc. The systems with the same order show the same dynamic characteristics regardless its type. A third order process simulator is designed as shown in Figure 1 to facilitate the application of the PD-I controller suggested in this paper to control a process relatively having bad dynamics.[11]

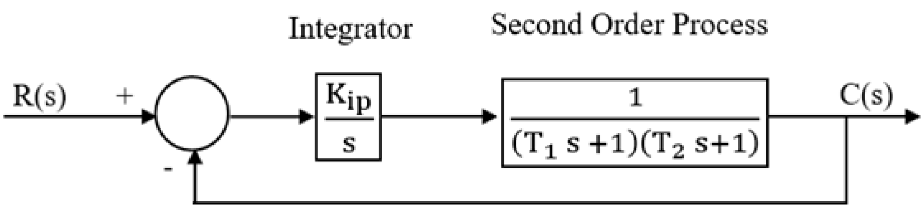

Figure 1: Block diagram of a third order process simulator.

The closed loop transfer function of the third order process shown in Figure 1 is given by:

$$\frac{C(s)}{R(s)} = \frac{\frac{K_{ip}}{T_1T_2}}{s^3+\left(\frac{T_1+T_2}{T_1T_2}\right)s^2+\left(\frac{1}{T_1T_2}\right)s+\frac{K_{ip}}{T_1T_2}} \qquad (1)$$

Where: K_{ip} is the integral gain of an electronic integrator

T_1 is the time constant of a first order process simulator.

T_2 is the time constant of a another first order process simulator.

The following set of process parameters are selected based on the process stability and its bad dynamics: K_{ip}= 0.5, T_1= 1 s, T_2= 5 s

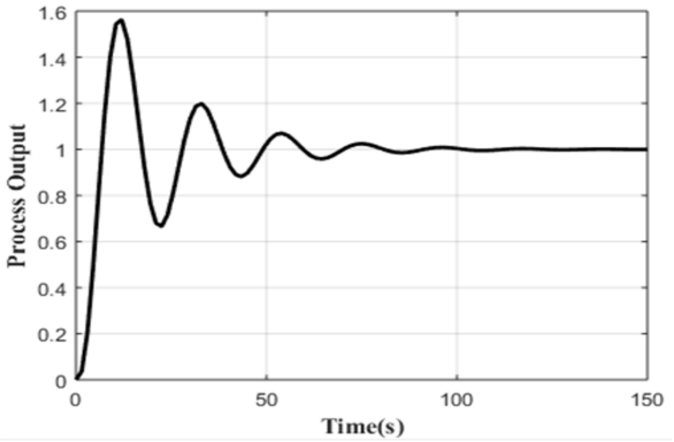

Figure 2 Unit Step time response of the third order process

The step time response of the third order process using the selected set of parameters is shown in Figure 2 as generated by MATLAB.

Controller

The PD-I Controller represents a new configuration of the PID controller belonging to the second generation of PID controllers and used by Prof. Galal Hassaan in 2018 to control underdamped second order processes.[5]

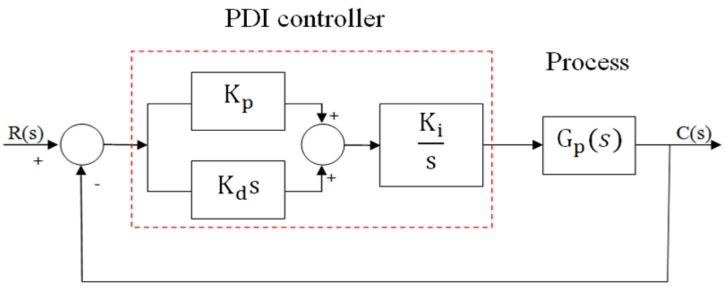

Figure shows the block diagram of a closed loop control system incorporating a PD-I controller and the controlled process.[5]

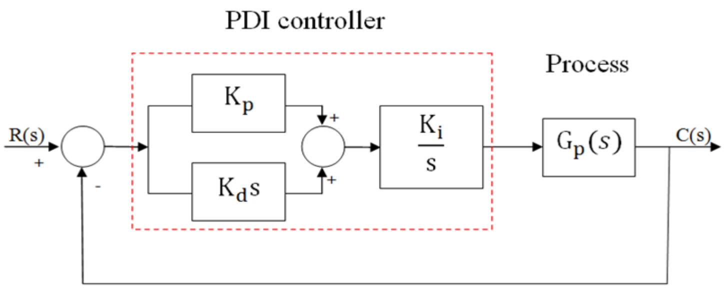

Figure 3: Block diagram of a control system using a PD-I.[5]

The parameters of the control system are as follows

K_p Controller proportional gain.

K_d Controller derivative gain.

K_i Controller integral gain.

$G_p(s)$ Transfer function of the third order process.

The closed loop transfer function of the control system, M(s) for reference input tracking using Figure 3 and equation 1 is:

$$M(s) = \frac{\frac{K_{ip}K_dK_i}{T_1T_2}s + \frac{K_{ip}K_pK_i}{T_1T_2}}{s^4 + \frac{T_1+T_2}{T_1T_2}s^3 + \frac{1}{T_1T_2}s^2 + \frac{K_{ip}+K_{ip}K_dK_i}{T_1T_2}s + \frac{K_{ip}K_pK_i}{T_1T_2}} \quad (2)$$

PD-I Controller Tuning

The PD-I Controller is tuned based on five objective functions: ISE, IAE, ITAE, ITSE and ISTSE. The objective functions depend on the error between the step time response of the control system and its steady state response. A MATLAB code based on the optimization toolbox of MATLAB is used to tune the controller through minimizing the objective functions subjected to a number of functional constraints using the command '*fmincon*' [12]. The objective functions used are.[12]

$ISE = \int_0^T e^2(t)dt$	**(3)**
$IAE = \int_0^T \lvert e(t)\rvert dt$	**(4)**
$ITAE = \int_0^T t\lvert e(t)\rvert dt$	**(5)**
$ITSE = \int_0^T te^2(t)dt$	**(6)**
$ISTSE = \int_0^T t^2e^2(t)dt$	**(7)**

The step response to a unit reference input is plotted using the '*step*' command of MATLAB.[13] The control system time-based specifications are extracted via using the MATLAB command '*stepinfo*'.[13] Figure 4 shows the control system unit step time response using the PD-I controller tuned using five objective functions. The time based specifications for the control system are given in Table 1.

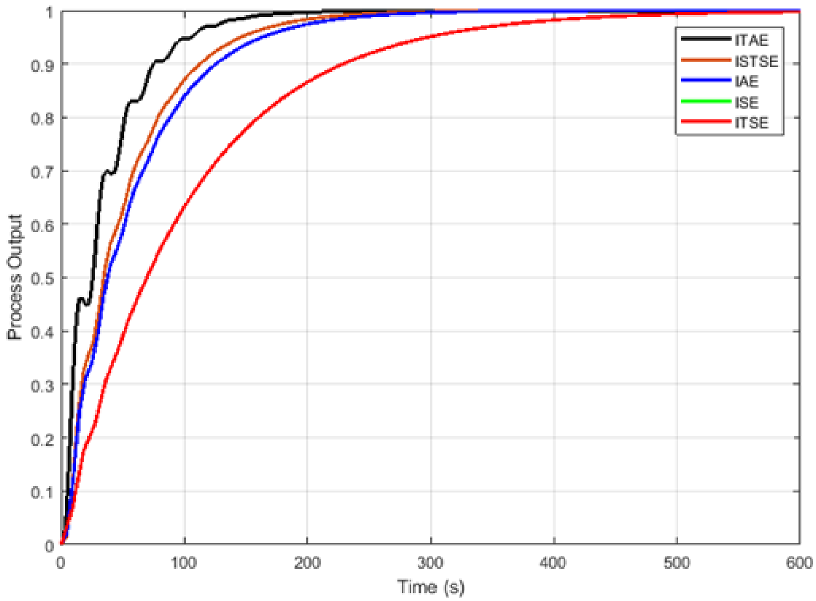

Figure 4 Unit step time response of the control system incorporating a Tuned PD-I Controller

Objective Functions / Control System Parameters	ITSE	ITAE	ISE	IAE	ISTSE
K_p	0.1	0.3	0.1	0.1	0.03
K_d	0.01	1	0.1	0.08	0.8
K_i	0.2	0.1	0.1	0.09	0.08
OS_{max} (%)	0	0	0	0	0
T_s (s)	190.3142	133.5132	388.4925	212.9792	1701.4807

It is clear from Figure 4 that the ITAE objective function provides the best controller tuning. The drawback in this step time response of the control system is that the step time response is not smooth and has certain irregularities which may be improved through using a filter after the integral control mode in Figure 3.

Checking Robustness of the PD-I controller

Robustness is one of the important characteristics in controller design. Through this section we will discuss and examine the PD-I controller robustness while controlling the proposed highly oscillating third order process under some uncertainty in its parameters. Any process under operation is supposed to have uncertainty due to operating conditions or components durability and lifetime. It is assumed that any process parameter varies within ± 20%. A simulation study using a specially written MATLAB code is applied to investigate the effect of the process parameters uncertainty on the performance of the control system.

The control system is considered robust in case if it has an acceptable change in its performance due to the process uncertainty or inaccuracy.[14] Lee and Na added the stability requirement to the robustness definition.[14],[15] Toscano added that the controller must be able to stabilize the control system for all the operating conditions.[16] In this paper, the assessment of the controller robustness and hence of the whole control system is based on the following:

- Assigning the process parameters.
- Tuning the controller using the MATLAB optimization Toolbox for the assigned process parameters.
- Assuming variation of the process parameters within the range ± 20 % of the assigned process parameters.
- Using the same tuned controller parameters, the step time response of the control system using the new process parameters is drawn and the control system performance is evaluated through the maximum percentage overshoot and the settling time.
- The frequency based relative stability parameters are also evaluated using the open-loop transfer function of the control system.
- The variation in process parameters is changed over the specified range and the procedure is repeated.

From the block diagram of Figure 3 , the control system open loop transfer function of the closed loop control system in hand, G(s) is driven and given by:

$$G(s) = \frac{\frac{K_{ip}K_dK_i}{T_1T_2}s + \frac{K_{ip}K_pK_i}{T_1T_2}}{s^4 + \frac{T_1+T_2}{T_1T_2}s^3 + \frac{1}{T_1T_2}s^2 + \frac{K_{ip}}{T_1T_2}s} \quad \textbf{(8)}$$

The effect of the variation in the process parameters on the time-based specifications of the control system using the tuned PD-I controller parameters is shown in Figure 2 and 6 for the settling time and maximum percentage overshoot respectively.

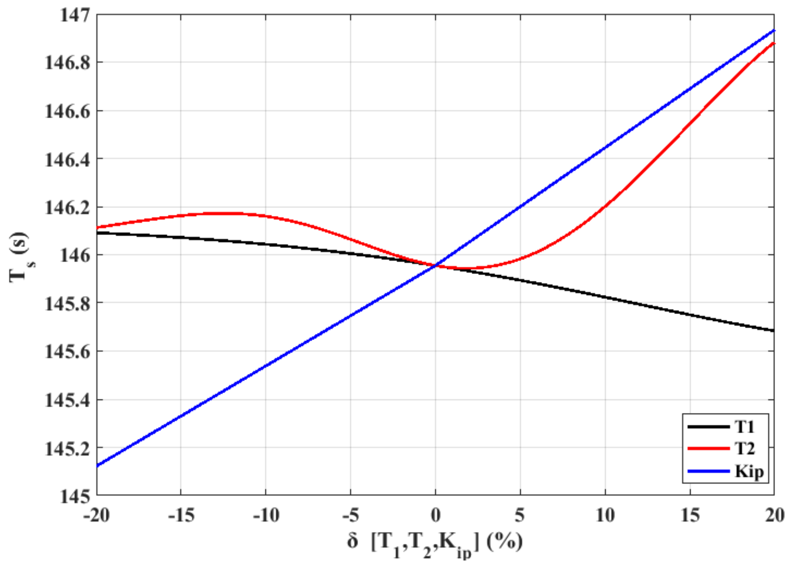

Figure 2: Effect of process parameters change on the control system settling time.

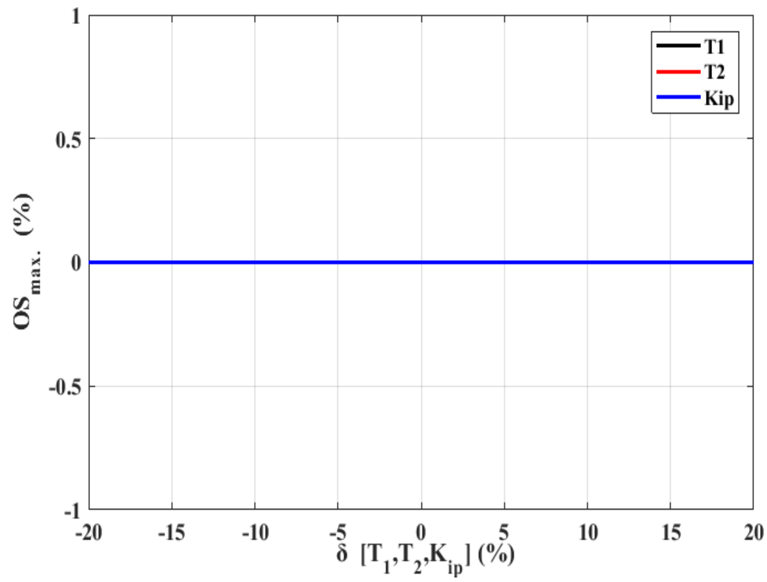

Figure 3: Effect of process parameters change on the control system maximum percentage overshoot.

As shown in Figure 2 and 6, the maximum effect of the process parameters uncertainty on the control system settling time is about one second and there is no effect on the maximum percentage overshoot.

The relative stability margins are investigated using the open loop transfers function in equation 8 and the MATLAB command "*margin*".[17]

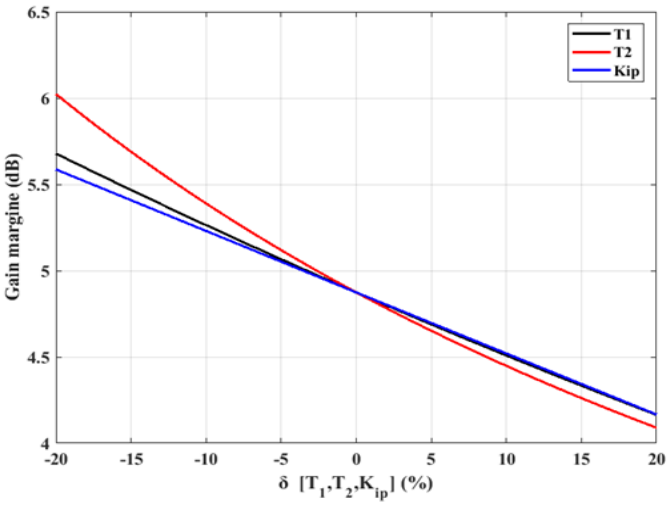

Figure 7 Effect of process parameters change on the gain margin of the control system

The effect of the process parameters uncertainty on the relative stability margin is shown in Figures 7 and 8 for the gain and phase margins respectively.

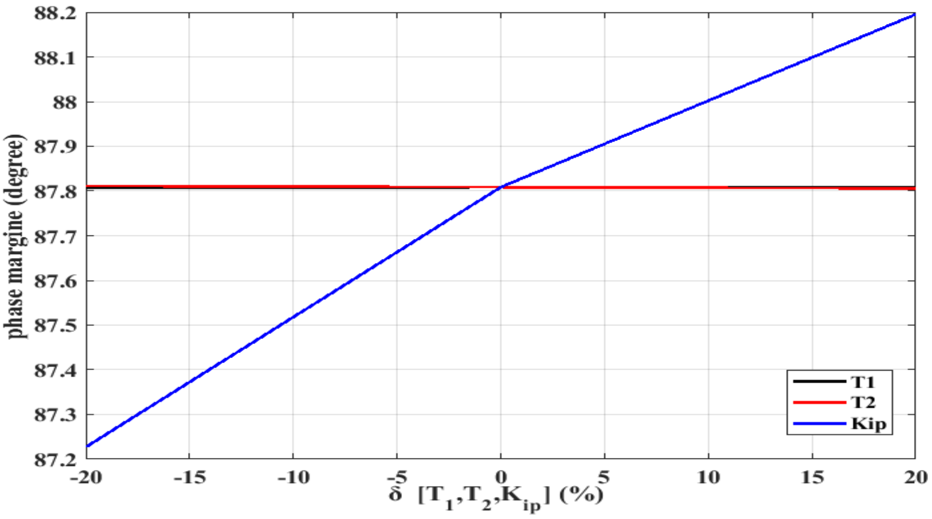

Figure 8: Effect of process parameters change on the phase margin of the control system.

As shown in Figures 7 and 8, the maximum effect of the process parameters uncertainty on the control system gain margin is about 1 dB and about 0.6 degree on the phase margin. According to Ogata,[18] for a control system with a good performance:

- Gain Margin has to be > 6 dB.
- Phase Margin: must be in the range: 30 ≤ PM ≤ 60 degrees.
- According to Lee and Man, the upper limit of the phase margin for a good performance can go up to 90 degrees.[15]

According to the above analysis

- The PD-I based control system is not robust considering the gain margin characteristic of the control system.
- The PD-I based control system is robust considering the phase margin characteristic of the control system.
- More investigations are required by suggesting the addition of a filter after the integral mode of the PD-I controller to be PDIF.[10]

CONCLUSION

- A PD-I controller from the second generation of PID controllers was used to control a highly oscillating third order process.
- The controller was tuned using the MATLAB optimization toolbox, error-based objective function and performance functional constraints.
- The step time response due to reference input tracking didn't show any kick with most of the objective functions used in the tuning process.
- The PD-I controller succeeded to overcome the high oscillation of the third order process, but the control system was sluggish.
- The PD-I controller was not robust considering the gain margin characteristics of the control system. However, it was robust considering the phase margin characteristics of the control system.

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BIOGRAPHY

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