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RESEARCH ARTICLE OPEN ACCESS

Tuning of a Feedforward 2DOF PID Controller to Control Second Order-Like Processes

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Abstract:

This research paper aims at investigating the use of a 2DOF PID controller to control second order-like processes. The controller is tuned using MATLAB control and optimization toolboxes. Using the suggested tuning technique, it is possible to eliminate completely the kick characteristic associated with PID controllers and produce a step-like step time response to set-point change. The effectiveness of using the 2DOF PID controller is examined by comparison with another tuning technique and another different two controllers (I-PD and PI-PD controllers)

Keywords — **Second order-like processes, 2DOF PID controller, controller tuning, MATLAB optimization toolbox, Control system performance.**

I. INTRODUCTION

A large number of processes can be considered as a second order process where a large number of controllers and/or compensators can be used for their control providing feedback control systems with high performance. Here, we propose a 2DOF PID control for this purpose providing outstanding advantages for the set-point tracking problems.

Taguchi and Araki (2000) outlined that a 2DOF PID controller is a 2 DOF controller whose serial compensator is a PID element and whose feedforward compensator is a PD element. They reported its analysis and formulae for its optimal tuning. They presented two block diagrams for control systems incorporating the 2DOF PID controller: one with feedforward type and the other with feedback type [1]. Araki and Taguchi (2003) surveyed important results about the 2DOF PID controllers and presented explanations about the effect of the 2DOF structure. They presented also an optimal tuning method for the 2DOF PID controllers for seven types of delayed processes [2], Jiang, Smith and Kitchen (2009) designed a 2DOF PID controller for an engine electronic throttle and tuned the PID controller parameters using iterative feedback tuning. They presented the 2DOF controller structure of the feedback type [3], Nemati and Ragheri (2010) generalized proposed a tuning method for PI controller in 2DOF structure for use a first order plus dead time process. Their tuning strategy was based on using Butterworth rules and genetic algorithm optimization. The 2DOF structure used based on using feedforward and feedback controllers[4], Vilanova, Alfaro and Arrieta (2011) presented a tuning approach for 2DOF PI and PID controllers used with first order plus dead time and second order plus dead time processes. They used a PI controller in the feedforward path just before the error detector of the control system and a PID controller in the feedback path. They investigated the robustness of the closed loop control system for both type of processes [5], Boujari, Tanha, Rahimian and Rahami (2012) studied the use of a 2DOF PID controller for active vibration control of structures. The controller structure they used was the use of a controller in the feedforward path after the main error detector and a feedback controller feeding a signal to a second error detector after the first controller [6] Alfaro and Vilanova (2013) presented the performance and robustness analysis of servo-control and regulatory control systems. They considered first order plus dead time and second order plus dead time processes. They developed a robust tuning method for 2DOF PID controllers [7]. Jimenez, Yam and Moctezuma (2014) presented a design methodology for a 2DOF PID controller for set point response, load disturbance and robustness to model uncertainty [8]. Choudhary (2015) in his Master of Technology Thesis presented an overview of designing and tuning of 2DOF PI and PID controllers for single and two tanks systems. He outlined that using a 2DOF PI and PID controller overcome the disadvantage of using conventional PI and PID controllers for set point tracking with disturbance rejection [9], Kumar and Patel (2015) proposed 2DOF PID controller for speed control of DC motor who gave better results compared to the conventional PID controller [10]. Hassaan (2015) investigated the use and tuning of a 2DOF PID-PI controller for disturbance rejection of a highly oscillating second order-like process. He outlined that the used 2DOF controller could compete well with PD-PI and PI-PD controllers [11]. Deshmukh (2016) tuned a 2DOF PID controller by using different PID tuning techniques and analysed the time domain respone specifications. He applied the 2DOF PID controller for a temperature control set-up. [12]. Leiva et. al. (2016) applied the enhanced normalized normal constrained method for the optimal tuning of 2DOF PID controllers. They applied their method to higher order linear process , to a nonlinear tank reactor and to a benchmark control system with three sources disturbances [13]. Pachauri, Singh and Rani (2018) proposed 2DOF PID controller for desired temperature control of bioreactor. They used the non-dominated sorted genetic algorithm II to tune the controller to regulate the temperature of the bioreactor in more robust and efficient manner compared to other controllers [14].

II. PROCESS

The controlled process is second-order-like process having the transfer function, $G_p(s)$:

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

Where:

ω_n = process natural frequency

ζ = process damping ratio

The damping ratio of the process classifies the process as an underdamped, critically damped or overdamped one.

III. THE 2DOF PID CONTROLLER

The structure of a 2DOF PID controller for the control of process is shown in Fig.1 [15]..

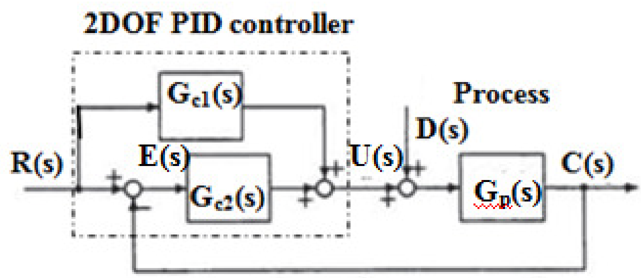

Fig.1 2DOF PID controller structure [15].

The 2DOF controller shown in Fig.1 has two sub-controllers: one in the feedforward path with R(s) as its input with $G_{c1}(s)$ transfer function and another sub-controller in the main forward path of the closed-loop control system with the error signal E(s) as its input with $G_{c2}(s)$ transfer function. The output signal of the controller is U(s) superimposed by a disturbance signal D(s) all fed to the process to be controlled. In our present work, the first sub-controller is selected as a PD controller while the second sub-controller is selected as a PID controller. The transfer functions of both sub-controllers are:

$$G_{c1}(s) = K_{pc1} + K_{d1}\, s \qquad (2)$$

And $$G_{c2}(s) = K_{pc2} + (K_i/s) + K_{d2}\, s \qquad (3)$$

Where:

It has the parameters:

- Proportional gains, K_{pc1} and K_{pc2}
- Derivative gains, K_{d1} and K_{d2}
- Integral gain, K_i

IV. CONTROL SYTEM TRANSFER FUNCTION

Using the block diagram of the closed-loop control system shown Fig.1 with R(s) as the reference input, and C(s) is the process output and the process transfer function of Eq.1 and the sub-controllers transfer functions of Eqs.2 and 3, the transfer function of the closed-loop control system for set-point tracking is M(s) = C(s)/R(s) given by:

$$M(s) = (b_0s^2 + b_1s + b_2) / (s^3 + a_1s^2 + a_2s+a_3) \quad (4)$$

Where:

$b_0 = \omega_n^2(K_{d1} + K_{d2})$
$b_1 = \omega_n^2(K_{pc1} + K_{pc2})$
$b_2 = \omega_n^2 K_i$
$a_1 = 2\zeta\omega_n + \omega_n^2 K_{d2}$
$a_2 = \omega_n^2 (1 + K_{pc2})$
$a_3 = \omega_n^2 K_i$

V. CONTROLLER TUNING AND SYTEM TIME RESPONSE

The controller has five parameters: K_{pc1}, K_{d1} , K_{pc2}, K_i and K_{d2} The controller parameters are tuned as follows:

- The control and optimization toolboxes of MATLAB are used to assign the five parameters of the controller [15].
- The integral of time multiplied by absolute error (ITAE) is chosen as an objective function for the optimization process.
- Three functional constraints are set for the closed-loop control system maximum percentage overshoot, settling time and a stability constraint derived from the Routh-Hurwitz criterion for control system stability.
- The step response of the closed-loop control system is plotted using the command '*step*' of MATLAB [16].
- The controller is tuned using the above approach for second order-like processes having equivalent damping ratio in the range: $0.05 \leq \zeta \leq 2$ and equivalent natural frequency in the range: $0.5 \leq \omega_n \leq 7.5$ rad/s.
- The optimal derivative gain of the second sub-controller K_{d2} was very close to an average value of 399.5 with 1.8034 standard deviation.
- The time-based specifications of the closed-loop control system are extracted using the MATLAB command '*stepinfo*' [17].
- The tuning parameters of the 2DOF PID controller and some of the performance measures of the closed-loop control system incorporating the controller and the second order-like process are given in Tables 1 through10.

TABLE 1

2DOF PID CONTROLLER TUNING FOR $\zeta = 0.05$

ω_n (rad/s)	0.5	1	2.5	5	7.5	10
K_{pc1}	0.5104	0.9406	0.9844	0.9984	0.9995	0.999
K_{d1}	0.0730	0.3980	0.0177	0.0182	0.0128	0.010
K_{pc2}	12.2004	23.157	54.741	17.327	10.283	0.614
K_i	48.9847	23.276	38.913	15.055	12.191	36.477
OS_{max} (%)	0	0	0	0	0	0
T_s(s)	0.0391	0.0098	0.0016	0.0004	0.0002	0.0001

TABLE 2

2DOF PID CONTROLLER TUNING FOR $\zeta = 0.1$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.7637	0.9190	0.9781	0.9984	0.9989
K_{d1}	0.1186	0.0618	0.0427	0.0374	0.0221
K_{pc2}	27.4344	54.6494	91.9209	86.4815	100.7430
K_i	23.6845	32.5932	54.4938	66.4815	23.5870
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0390	0.0097	0.0016	0.0004	0.0002

TABLE 3

2DOF PID CONTROLLER TUNING FOR $\zeta = 0.25$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.6664	0.9700	0.9951	0.9984	0.9994
K_{d1}	0.3473	0.4716	0.1955	0.0981	0.0661
K_{pc2}	64.9437	10.3937	10.2304	17.9954	11.9503
K_i	33.5366	12.0272	12.1318	15.5931	12.8891
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0389	0.0098	0.0016	0.0004	0.0002

TABLE 4

2DOF PID CONTROLLER TUNING FOR $\zeta = 0.5$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.5311	0.9362	0.9888	0.9974	0.9985
K_{d1}	0.7509	0.7428	0.3589	0.1898	0.1327
K_{pc2}	125.5882	102.1390	101.3343	100.9587	12.9955
K_i	47.3447	25.5581	27.9620	26.3118	33.9675
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0387	0.0098	0.0016	0.0004	0.0002

TABLE 5

2DOF PID CONTROLLER TUNING FOR $\zeta = 0.75$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.3393	0.9366	0.9912	0.9977	0.9993
K_{d1}	1.7933	1.2432	0.5934	0.2974	0.1991
K_{pc2}	121.1981	102.1320	15.5913	24.1861	19.828
K_i	66.5474	25.4220	21.9719	22.2242	16.181
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0388	0.0097	0.0016	0.0004	0.0002

TABLE 6

2DOF PID CONTROLLER TUNING FOR $\zeta = 1$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.3417	0.6722	0.9939	0.9980	0.9993
K_{d1}	3.6664	1.6712	0.7852	0.3973	0.2655
K_{pc2}	33.3955	131.7415	36.0373	23.1513	25.6138
K_i	66.5629	131.9953	15.1951	19.7567	15.6197
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0387	0.0097	0.0016	0.0004	0.00017

TABLE 7

2DOF PID CONTROLLER TUNING FOR $\zeta = 1.25$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.7918	0.9344	0.9741	0.9933	0.9971
K_{d1}	3.9953	2.2446	0.9858	0.4963	0.3317
K_{pc2}	100.7490	101.7824	34.5420	35.8946	35.498
K_i	21.0440	26.3982	64.9956	66.6118	65.111
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0387	0.0097	0.0016	0.0004	0.0002

TABLE 8

2DOF PID CONTROLLER TUNING FOR $\zeta = 1.5$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.7966	0.8374	0.9726	0.9935	0.9971
K_{d1}	5.0026	2.9151	1.1831	0.5964	0.3985
.K_{pc2}	100.2015	33.3704	41.2596	35.5714	33.7269
K_i	20.5994	65.5217	68.5901	64.8318	64.8766
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0386	0.0097	0.0016	0.0004	0.00017

TABLE 9

2DOF PID CONTROLLER TUNING FOR $\zeta = 1.75$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.7490	0.8227	0.9725	0.9932	0.9970
K_{d1}	6.0986	3.3765	1.3841	0.6964	0.4651
.K_{pc2}	90.9161	48.7758	38.7320	34.9554	34.9731
K_i	25.5280	71.1698	68.7292	67.6642	67.1365
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0385	0.0097	0.0016	0.0004	0.00017

TABLE 10

2DOF PID CONTROLLER TUNING FOR $\zeta = 2$

ω_n (rad/s)	0.5	1	2.5	5	7.5
K_{pc1}	0.4620	0.9460	0.9887	0.9973	0.9989
K_{d1}	6.8691	3.7489	1.5592	0.7897	0.5287
.K_{pc2}	114.5838	100.4335	101.0191	98.7088	102.3274
K_i	54.7288	21.8050	28.1475	26.3999	23.6559
OS_{max} (%)	0	0	0	0	0
T_s(s)	0.0385	0.0097	0.0016	0.0004	0.00017

- The step time response of the control system for set-point tracking for a second order-like process using two sets of process parameters and using a tuned 2DOF PID controller using Tables 1 and 10 is shown in Fig.2.

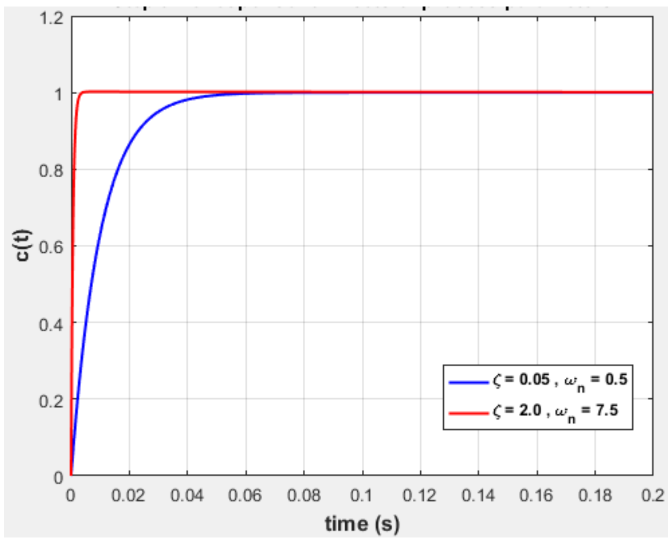

Fig.2 2DOF PID controlled second order process

- The settling time of the step response to set point change is independent on the process damping ratio but depends exponentially on its natural frequency. This dependence is presented graphically in Fig.3.

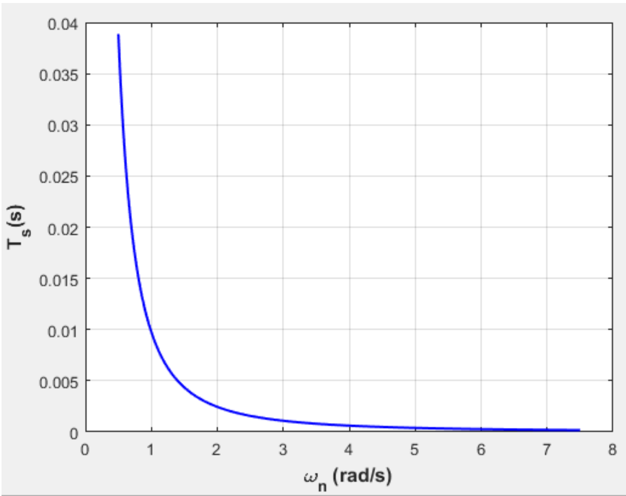

Fig.3 Effect of process natural frequency on settling time.

VI. COMPARIZON WITH MINIMUM ITAE STANDARD FORMS TUNING

- The parameters of the 2DOF PID controller is tuned using the minimum ITAE standard forms of Graham and Lathrop [18]. The resulting controller parameters are:

$$K_{pc2} = 103.9834$$
$$K_i = 48.9847$$
$$K_{d2} = 27.1831$$

- The parameters of the PD sub-controller are taken as tuned in Table 1.
- The step response of the closed loop control system incorporating the 2DOF PID controller and the process is shown in Fig.4 for both tuning techniques.

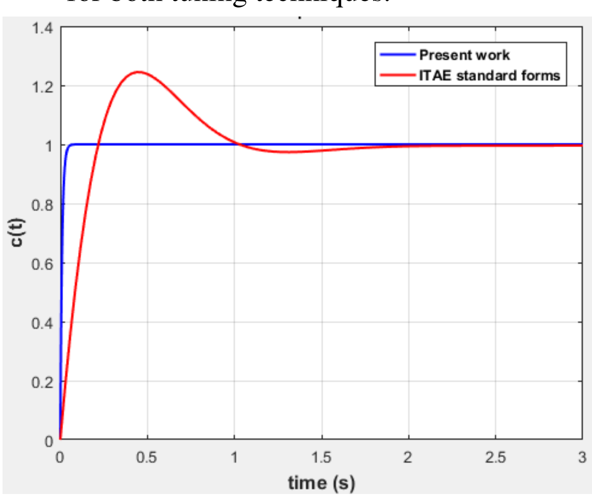

Fig.4 Comparison between two tuning techniques.

- The performance characteristics of the control system for both tuning techniques are as follows:
  - The maximum percentage overshoot is zero using the presented tuning technique compared with 24.47 % using the minimum ITAE standard forms of Graham and Lathrop.
  - The settling time (within ± 2 % band) is 0.039 s compared with 1.53 s using the minimum ITAE standard forms of Graham and Lathrop.

VII. COMPARIZON WITH OTHER CONTROLLERS

- To investigate the effecting of the studied controller in suppressing the high oscillations of the controlled process for set-point change, it was compared with using an I-PD controller [19] and a PI-PD controller [20].
- The I-PD controller was tuned using an ISE objective function producing the tuned controller parameters [19]:

$$K_{pc} = 1.7523$$
$$K_i = 5.3314$$
$$K_d = 0.1113$$

- The PI-PD controller was tuned using an ISTSE objective function producing the tuned controller parameters:

$$K_c = 18.9517$$
$$K_f = 1.0037$$
$$K_i = 44.9216$$
$$K_d = 0.7119$$

- The step response of the closed loop control system incorporating the controller and the highly oscillating process for a unit step set-point change is shown in Fig.5.

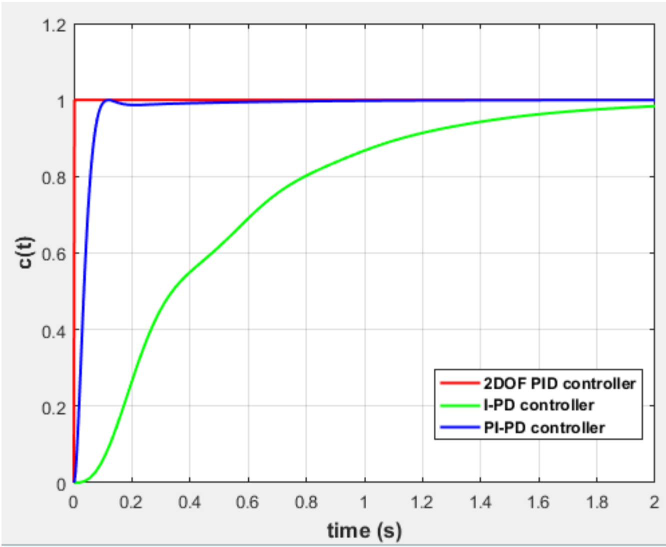

Fig.5 Comparison between three controllers.

- The time based characteristics of the control system using the three controllers are compared in Table 11.

TABLE 11
CHARACTERISTICS COMPARISON USING THREE CONTROLLERS

Controller	2DOF PID	I-PD	PI-PD
OS_{max} (%)	0	0	0
T_s (s)	0.0001	1.8975	0.0920

VIII. Conclusion

- The tuning process of a 2DOF PID controller for use with second-order-like processes was investigated.
- A PD and PID sub-controllers were used as elements of the 2DOF PID controller.
- The 2DOF PID controller was proposed in this paper to control second order-like processes of damping ratio between 0.05 and 2 and natural frequency between 0.5 and 7.5 rad/s.
- The 2DOF PID controller had 5 gain parameters to be tuned for optimal performance of the closed loop control system incorporating the controller and the process.
- The 2DOF PID controller was tuned using the optimization and control toolboxes of MATLAB.
- The controller succeeded to suppress completely the oscillations of the underdamped process to step input change and compensate their slow step time response for overdamped second order-like processes.
- All the tuning parameters of the 2DOF PID controller generated step time response with zero overshoot and settling time less than 0.04 s.
- The settling time of the closed loop control system with set-point change decreased exponentially with the natural frequency of the second order process, while its damping ratio had no effect on it.
- The tuning process of the 2DOF PID controller was based on using the optimization and control toolboxes of the MATLAB as a constrained optimization problem.
- An ITAE objective function and three functional constraints were used to tune the controller and maintain a stable control system with good performance measures.
- The used tuning technique was compared with a tuning technique based on the minimum ITAE standard forms.
- The effectiveness of the proposed 2DOF PID controller in controlling a highly oscillating second order process was compared with using an I-PD and PI-PD controllers. The 2DOF PID controller proved to be superior compared with the other two controllers.

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BIOGRAPHY

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