International Journal of Engineering and Techniques - Volume 10 Issue 3, May 2024

RESEARCH ARTICLE OPEN ACCESS

Thermoplastics Injection Molding Machine Control, Part II: Barrel Temperature Control using PD-PI, PI-PD and 2DOF-2 Controllers Compared with ANN-PI Controller

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Abstract:
This paper investigates the tuning of PD-PI, PI-PD and 2DOF-2 controllers when used to control the temperature of an injection molding machine barrel. The controllers are tuned using MATLAB optimization toolbox and the ITAE performance indices. The tuning results are presented and applied to generate the unit step time response for both reference and disturbance inputs. A novel technique is used to improve the disturbance rejection associated with the proposed controllers. The characteristics of the step time responses are compared with those of an ANN-PI controller from previous work and presented in graphical and tabulated form. The best controller for both reference and disturbance inputs is assigned.
Keywords — **Thermoplastics injection molding machine, Barrel temperature control, PD-PI controller, PI-PD controller, 2DOF-2 controller, controller tuning.**

I. INTRODUCTION

Barrel temperature is one of the injection molding machine operating variable that changes from plastic material to another and affects the quality of the produced elements. There are various controlling techniques to control this variable and produce accepted performance for the control system. The objective of this research work is to investigate the application of some of the controllers from the second generation of PID controllers, tune them and compare their performance with one of the modern controllers (ANN-PI). Here are some of the research efforts regarding this subject:

Dubay, Diduch and Li (2004) presented an approach for temperature control of an injection molding machine using a model predictive control strategy. They used a number of SISO model predictive controllers each associated with a particular temperature zone. They applied their proposed controller on a 150 ton injection molding machine [1]. Wang and Wu (2006) proposed an approach to model and control the temperature of the barrel of an injection molding machine. Their mathematical model was based on Takagi-Sugero fuzzy system. They integrated the thermal model into internal model controller to control the barrel temperature showing excellent performance in the step time response [2]. Yao, Gao and Allgower (2008) studied the problem of operation transition between idle and operation states in injection molding machines. They presented a combined strategy using a feedback controller and an iterative learning feedforward controller to act with this transition problem of injection molding. They claimed that their control strategy provided superior performance compared with the conventional feedback controller [3].

Prabha, Rao and Krishna (2011) proposed an effective PID controller design using fuzzy logic. They compared the performance of the fuzzy logic designed PID controller with the conventional PID controller and fuzzy logic controller [4]. Sokolova, Prasad and Balakrishnan (2012) used an I-PD controller to control the temperature in each heating zone of the barrel of the injection molding machine instead of the conventional PID controller. They used particle swarm optimization to tune the I-PD controller reducing settling time and maximum overshoot compared with conventional PID controllers [5]. Wei (2013) studied an effective controller design to overcome the problem of non-linearity, large inertia and time variation of the temperature process of the injection molding machine. He used a PID controller for this purpose [6].

He and Shi (2015) used a PID neural network control to control the temperature of an injection molding machine and compared with conventional PID control through MATLAB simulation. They outlined that the PID neural network controller had strong ability to adapt working conditions and exhibit interference [7]. Agrawal and Gubta (2016) presented a technique for a linear fuzzy controller to control temperature in an injection molding machine. They used a first-order model mathematical with time delay for the barrel heater with 3 s delay and 144 s time constant. They presented the step time response for reference input tracking using both conventional PID and their proposed fuzzy logic controller [8].

Khomenko, Veligorskyi, Chakirov and Vagapov (2019) proposed an approach to control the temperature of an injection molding machine. They proposed an ANN-based temperature controller design based on a combination of a classical ANN and an integrator. They claimed that their controller provided fast temperature response with zero steady-state error for bar, nozzle and cartridge heaters. They compared the application of their controller with a conventional PID controller used with the same temperature process. They provided process linear models for the stated three types of barrel heaters [9]. Veligorskyi, Khomenko, Chakirov and Vagapov (2020) designed a combined ANN and PID temperature controller for injection molding machines. Their proposed technique was based on the integration of a conventional PI controller and a multi-layer ANN. Their proposed controller resulted in fast transients and accurate steady-state conditions. They applied the proposed controller to various types of heaters using MATLAB/Simulink [10].

Oenjoyo and Tan (2022) applied PID control to control the barrel and pneumatic of the injection molding machine. They claimed that the temperature target accuracy of the obtained control system was 90 to 95 % [11]. Hu and Wu (2023) designed an expert adjustable fuzzy control strategy to optimize the barrel temperature control system through combination of PID control, expert control and fuzzy control. They claimed that through simulation, their proposed technique could reduce the maximum overshoot by 3.1 %, settling time by 34 s. They used a heater transfer function in the form of a delayed first-order model having 20 s delay time and 26.3 s time constant [12]. Pan et al. (2024) proposed a barrel heating control method based on generalized predictive control with real time excess heat prediction model. Their proposed method could improve temperature control accuracy by 85.3 and 78.9 % compared with PID and GPC (generalized predictive control) [13].

II. THE CONTROLLED PROCESS

The controlled process is an injection molding machine with barrel heaters of the cartridge type. The open-loop transfer function of the barrel temperature with cartridge heater, $G_p(s)$ is given by [9]:

$$G_p(s) = 1694 / (53506s^2 + 547s + 1) \quad (1)$$

Eq.1 is used to plot the unit-step time response of the barrel temperature using the MATLAB command '*step*' [14] which is shown in Fig.1.

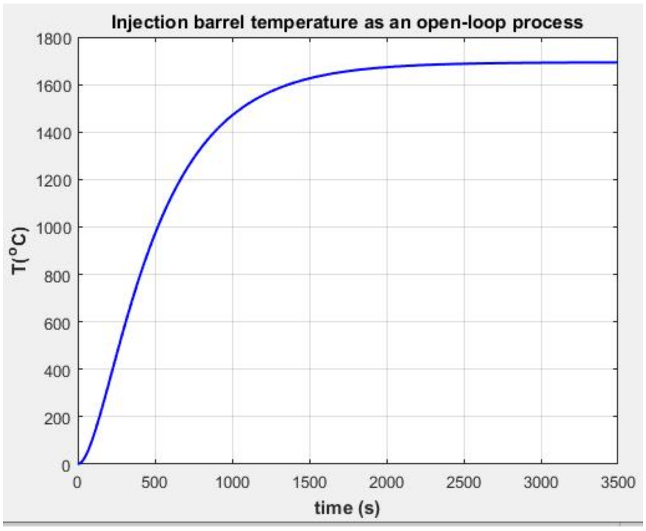

Fig.1 Step time response of the barrel temperature process.

Fig.1 reveals the following dynamic characteristics of the barrel temperature under study:

- Maximum overshoot: zero
- Settling time: 1786 s
- Steady-state error: -1692.4 °C

This is another example of bad processes that has to be controlled to overcome its bad dynamics of very large settling time and steady-state characteristics. Any proposed controller has to overcome those challenges and provide step response without any steady-state error and with fast time response (minimum settling time).

III. BARREL TEMPERATURE CONTROL USING A PD-PI CONTROLLER

- The PD-PI controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation of PID controllers. The author used PD-PI control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [15], integrating plus time delay process [16], delayed double integrating process [17], overdamped second-order processes [18], fourth-order blending process [19], coupled dual tanks [20], internal humidity of a greenhouse [21], rocket pitch angle [22], liquefied natural gas tank pressure [23], liquefied natural gas tank level [24], boiler temperature [25], boiler drum water level [26], furnace temperature [27], electro-hydraulic drive [28], rolling strip thickness [29] and injection molding mold temperature [30].
- The two elements of the PD-PI controller (PD and PI control modes) are set in cascade in the forward path of the block diagram of the barrel temperature control system just after the error detector.
- The transfer function of the PD-PI controller is given by [21]:

$$G_{PDPI}(s)=[K_dK_{pc2}s^2+(K_{pc1}K_{pc2}+K_dK_i)s+K_{pc1}K_i]/s \quad (2)$$

Where:

K_{pc1} = proportional gain of the PD-control mode

K_d = derivative gain of the PD-control mode

K_{pc2} = proportional gain of the PI-control mode

K_i = integral gain of the PI-control mode

- The controller has four gain parameters which have to be tuned for optimum performance for reference track input and good performance for the purpose of disturbance rejection.
- The unit step time response of the control system, c(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [14].
- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ITAE performance index [31] is minimised using the MATLAB optimization toolbox [32].
- Minimizing the error function ITAE reveals the optimal gain parameters of the controller.
- The PD-PI controller tuning technique reveals the following tuned controller parameters:

K_{pc1} = -0.017932 ; K_d = 109.59505

K_{pc2} = 107.70482 ; K_i = 0.0025372 (3)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PD-PI controller tuned gain parameters in Eq.3 and its transfer functions is shown in Fig.2.

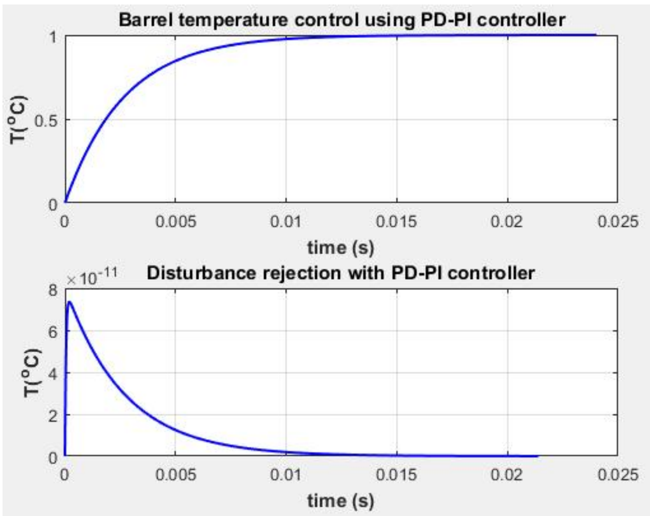

Fig.2 Step time response of the PD-PI controlled barrel temperature.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: zero
  - Settling time: 0.0105 s
  - It is similar to an ideal step.
- For disturbance rejection using the tuned PD-PI controller:

- Maximum step time response: 7.34×10^{-11}
- Minimum step time response: zero
- Settling time (with filter): 0.015 s
- It has ultimate disturbance rejection.

IV. BARREL TEMPERATURE CONTROL USING A PI-PD CONTROLLER

- The PI-PD controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used PI-PD control to control a variety of industrial processes with bad dynamics such as: highly oscillating second-order process [15], third-order process [34], greenhouse humidity [21], fourth-order blending process [19], boost-glide rocket engine [35] and BLDC motor [36], boiler drum water level [26], electro-hydraulic drive [28] and rolling strip thickness [29].
- The block diagram of a control system incorporating a PI-PD controller controlling the boiler-drum water level is shown in Fig.3 [29].

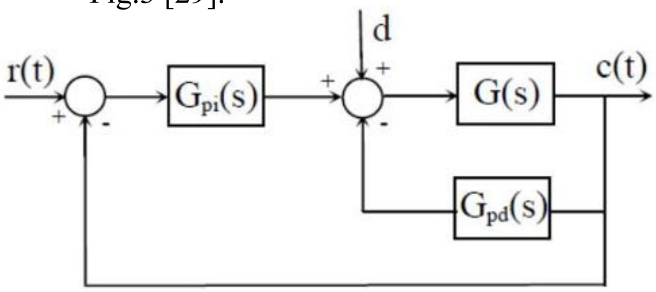

Fig.3 Block diagram of PI-PD controlled process [29].

- The PI-PD controller is composed of two elements: PI-control-mode in the forward path receiving its input from the error detector of the control system and a PD-control-mode in the feedback path of an internal loop with the controlled process.
- The PI-PD controller elements have the transfer functions:

$G_{PI}(s) = K_{pc1}+(K_i/s)$

And $G_{PD}(s) = K_{pc2}+K_d s$ (4)

- K_{pc1}, K_i, K_{pc2} and K_d are the four controller parameters gains to be tuned to adjust the performance of the closed-loop control system.
- The transfer functions of the closed-loop control system in Fig.3 are derived from the block diagram using Eqs.1 for the process and 4 for the PI-PD controller for both inputs R(s) and D(s).
- The unit step time response of the control system, c(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [14].
- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ITAE performance index [31] is minimised using the MATLAB optimization toolbox [32].
- Minimizing the error function ITAE reveals the following optimal gain parameters of the PI-PD controller:

$K_{pc1} = 0.144668$; $K_i = 0.005563$

$K_{pc2} = 0.127309$; $K_d = 3.53852$ (5)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the PI-PD controller tuned gain parameters in Eq.5 and shown in Fig.4.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 0.57
  - Settling time: 47.63 s
- For disturbance rejection using the tuned PI-PD controller:
  - Maximum step time response: 7.91×10^{-11}
  - Minimum step time response: -2.33×10^{-11}
  - Settling time (with using filter): 120 s

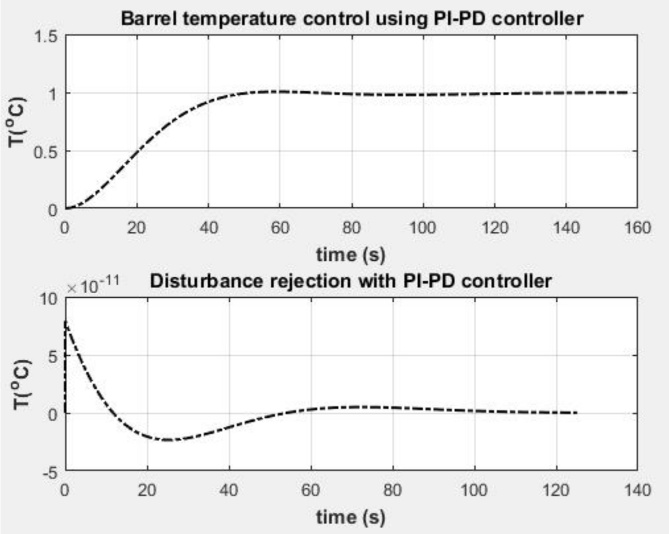

Fig.4 Step time response of the PI-PD controlled barrel temperature.

V. BARREL TEMPERATURE CONTROL USING A 2DOF-2 CONTROLLER

- The 2DOF controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation PID controllers. The author used different structures of 2DOF control to control a variety of industrial processes with bad dynamics such as: liquefied natural gas pressure control [23], liquefied natural gas level control [24], boost-glide rocket engine [35], BLDC motor control [36], boiler-drum water level [26], highly oscillating second-order process [33], delayed double integrating processes [38], second-order-like processes [39], furnace temperature [27], gas turbine speed [40], greenhouse temperature control [41], LNG tank pressure [23], LNG tank level [24], boiler temperature [25], boiler drum water level [26], furnace temperature [27], electro-hydraulic drive [28], rolling strip thickness [29] and molding machine mold temperature [30].
- The block diagram of a control system incorporating a 2DOF-structure 2 controller (denoted as 2DOF-2) proposed to control the barrel temperature is shown in Fig.5 [40].

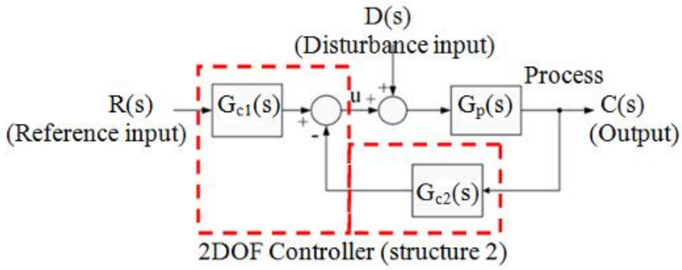

Fig.5 Block diagram of 2DOF-2 controlled process [40].

- The 2DOF-2 controller is composed of two elements: PI-control-mode of $G_{c1}(s)$ transfer function in a feedforward loop starting from the reference input and providing the control signal to the controlled process and a PID-control mode of $G_{c2}(s)$ transfer function in the feedback path of the control system.
- The 2DOF-2 controller elements have the transfer functions:

$G_{c1}(s) = K_{pc1} + (K_i/s)$

And $G_{c2}(s) = K_{pc2} + (K_i/s) + K_d s$ (6)

- K_{pc1}, K_i, K_{pc2} and K_d are the four controller parameters gains to be tuned to adjust the performance of the closed-loop control system.
- The transfer functions of the closed-loop control system in Fig.5 are derived from the block diagram using Eqs.1 for the process and 5 for the 2DOF-2 controller for both inputs R(s) and D(s).
- The unit step time response of the control system, c(t) for a reference input is obtained using the closed loop transfer function derived from the block diagram of the control system with zero disturbance and the '*step*' command of MATLAB [14].
- An error signal e(t) of the control system for a unit step input is assigned as: 1 – c(t) for a control system with unit feedback elements.
- The ITAE performance index is minimised using the MATLAB optimization toolbox [32].
- Minimizing the error function ITAE reveals the following optimal gain parameters of the 2DOF-2 controller:

$K_{pc1} = 0.119860$; $K_i = 0.131575$

$K_{pc2} = 1.739854$; $K_d = 6.861122$ (7)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [14] using the 2DOF-2 controller tuned gain parameters in Eq.7 and shown in Fig.6.

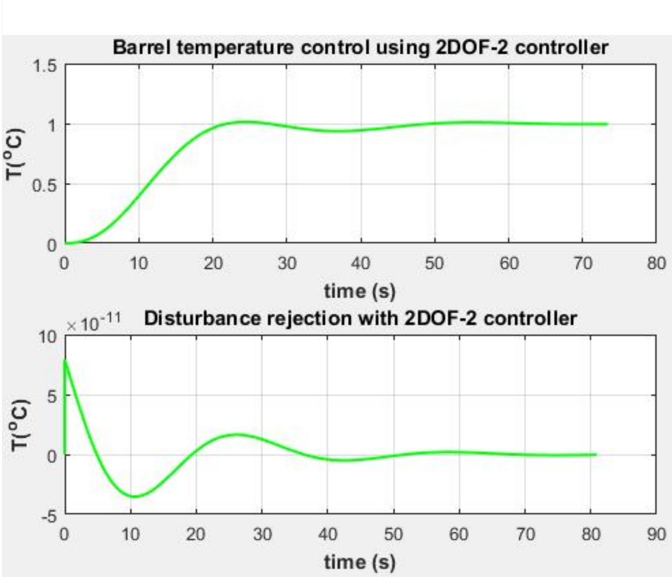

Fig.6 Step time response of the 2DOF-2 controlled barrel temperature.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 1.84 %
  - Settling time: 46 s
- For disturbance rejection using the tuned 2DOF-2 controller:
  - Maximum step time response: 2.91×10^{-11}
  - Minimum step time response: -3.53×10^{-11}
  - Settling time (with filter): 70 s

VI. COMPARISON OF TIME BASED CHARACTERISTICS

- Graphical comparison for both reference and disturbance inputs: Presented in Figs.7 and 8.
- Numerical comparison for the time-based characteristics of the step time response for reference input and disturbance input of the control system with the three investigated controllers (PD-PI, PI-PD and 2DOF-2) proposed in this work to control the barrel temperature of an injection molding machine is presented in Tables 1 and 2 with comparison with the application of a an ANN-PI controller used to control the same process [9].

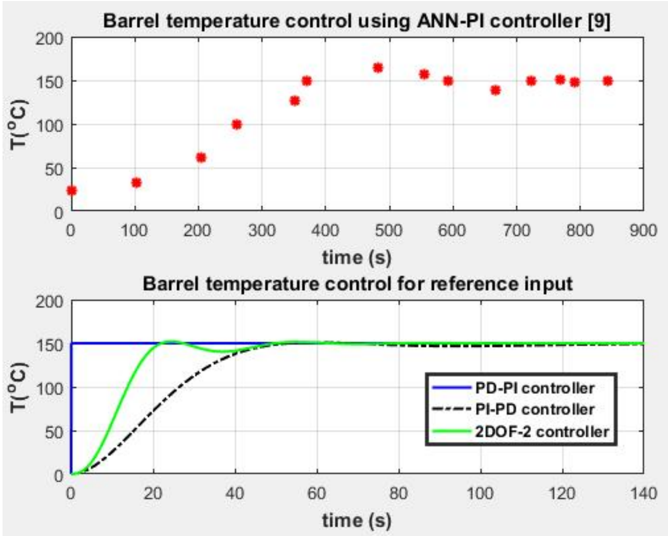

Fig.7 Step reference input time response comparison for barrel temperature control.

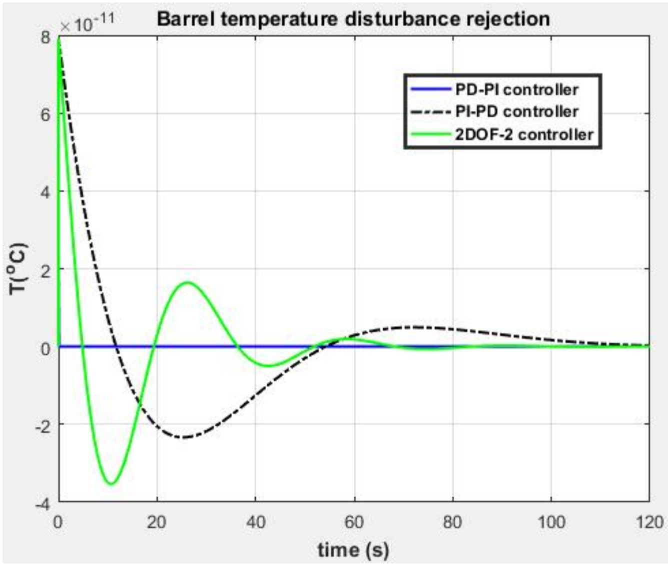

Fig.8 Step disturbance input time response comparison for barrel temperature control.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF THE BARREL TEMPERATURE

Controller	ANN-PI [9]	PD-PI	PI-PD	2DOF-2
OS_{max} (%)	9.8	0	0.57	1.84
T_s (s)	700	0.0105	47.63	46

TABLE 2
TIME-BASED CHARACTERISTICS WITH DISTURBANCE INPUT REJECTION

Controller	PD-PI	PI-PD	2DOF-2
Maximum time response (°C)	3.34×10^{-11}	7.91×10^{-11}	7.91×10^{-11}
Minimum time response (°C)	0	-2.33×10^{-11}	-3.53×10^{-11}
Settling time to zero (s, approximate)	0.015	120	70

VII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of PD-PI, PI-PD and 2DOF-2 controllers used to control the barrel temperature of an injection molding machine.
- The controlled process was a stable one with bad dynamics of very large settling time and very sensitive output to its reference input putting more challenges of the proposed controllers.
- The three controllers were tuned using the MATLAB optimization toolbox with an ITAE performance index aiming at providing a good dynamic performance for the control system for both reference and disturbance inputs.
- The three proposed controllers were compared with ANN-PI controller proposed to control the same process [9].
- The PD-PI controller succeeded to eliminate completely the maximum percentage overshoot compared with 9.8 % for the ANN-PI controller and succeeded to reduce the disturbance effect on the process output to a maximum value of 3.34×10^{-11} °C which is almost zero.
- The PI-PD controller succeeded to reduce the maximum percentage overshoot to 0.57 % compare with 9.8 % for the ANN-PI controller and provided almost negligible disturbance effect on process output through using a high-pass second-order filter.
- The 2DOF-2 controller succeeded to reduce the maximum percentage overshoot to 1.84 % compare with 9.8 % for the ANN-PI controller and provided almost negligible disturbance effect on process output through using a high-pass second-order filter.
- The PD-PI controller was selected as the best controller regarding reference input tracking and disturbance rejection. It provided an ideal step-wise time response compared with the other investigated controllers.

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DEDICATION

Prof. Ali Mostafa Mosharrafa

- A distinguished Egyptian mathematician born in 11th July 1898.
- Had his B.Sc. in 1920 from the University of Nottingham, UK.
- Had his Ph.D. in 1923 from the King's College London.
- He was awarded the degree of Doctor of Science in 1924 (the first Egyptian and 11th scientist in the world to have this degree).
- He became a 'Professor of Applied Mathematics' in 1926 in the Faculty of Science, Cairo University.
- He became the dean of the Faculty of Science of Cairo University in 1936 until his death in 1950.
- He published 25 papers on 'quantum theory', 'theory of relatively' and 'relation between radiation and matter'.
- He published 12 scientific books on 'relatively' and 'mathematics'.
- He was interested in the history of science specially the contribution of Arabic scientists in middle Ages.
- He published with Morsi Ahmed (one of his students) al-Khawarizmi book: The compendious book on calculation by completion and balancing (كتاب الجبر و المقابلة).
- He was against the use of atomic energy in war.
- His family initiated an annual award carrying his name to be given to the cleverest student in mathematics.
- How great you were Prof. Mosharrafa and how great was your family.
- Please accept my dedication to you.

BIOGRAPHY

Galal Ali Hassaan

- Emeritus Professor of System Dynamics and Automatic Control.
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