International Journal of Research Publication and Reviews, Vol 5, no 5, pp 4387-4398 May 2024

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Thermoplastics Molding Machine Control, Part III: Cavity Gate Pressure Control using I-PD, PD-PI, 2DOF-2 Controllers and an I-P Compensator compared with a PID Controller

Galal Ali Hassaan

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

A B S T R A C T

This research paper investigates the control of cavity gate pressure of an injection molding machine using I-PD, PD-PI and 2DOF-2 controllers and I-P compensator from the second generation of control controllers/compensators. The controllers and compensator are tuned using the MATLAB optimization toolbox and an ITAE performance index. The performance of the control system using the proposed controllers/compensator is compared with the performance using a PID controller from a previous work. The comparison takes the form of graphical and quantitative form revealing the best controller/compensator suitable to control the cavity gate pressure with the best performance characteristics.

Keywords: Injection molding cavity gate pressure control, I-PD controller, PD-PI controller, 2DOF-2 controller, I-P compensator, controller/compensator tuning, control system performance.

1. Introduction

This research paper deals with the control of the cavity gate pressure of an injection molding machine which is the third paper in a series aiming at investigating the proper control of the injection molding machine variables. The series started with the control of the mold temperature [1] followed by the control of the barrel temperature of the injection molding machine [2]. The start is with introducing some of the efforts world-wise about nozzle-mold pressure control. Abu-Fara, Kamal and Patterson, 1985 presented simple pseudo-steady state model between hydraulic and nozzle pressures of an injection molding machine. They used discrete PI and PID controllers tuned using ITAE performance index. The PID controller showed better performance than the PI controller in the nozzle pressure control simulation [3]. Kamal, Patterson, Conley, Abu-Fara and Lohfink, 1987 evaluated the hydraulic, nozzle and cavity pressures in an injection molding machine. Pseudo random binary sequences were employed to obtain and compare the dynamic models of the three variables. They used the derived models to select optimal controllers for the selected machine variables. They investigated the use of Dahlin and PID digital controllers and presented the step time response of the control system for the nozzle pressure [4]. Rafizadeh, 1996 outlined that mold cavity pressure plays an important role in affecting the quality of the molded articles. He investigated the dynamics of the cavity pressure during the filling stage where he derived a fifth-order transfer function for the cavity pressure. He designed an adaptive PI, PID and IMC controllers for cavity pressure control. He applied the same approach for the packing phase where a sixth-order transfer function was derived and the same controllers were applied [5].

Villalobos, 2001 applied open-loop experiments to determine appropriate model for the pressure control of an injection machine cavity. He applied a self-tuning algorithm with an observer to control the mold cavity pressure. He tuned the controller parameters using the pole-location technique [6]. Huang, 2007 presented a method for accurate decision concerning the ideal switching time for injection molding. He adopted a grey model (GM1,1) to to predict the volumetric filling point when monitoring the cavity pressure profile in each cycle. He applied the cavity pressure profile for a precise switchover control and as indicator of product quality. After experimental verification, his technique yielded a more uniform product weight [7]. Wang, Ying, Chen and Feng, 2010 presented an energy saving design for servo injection machine system with servo motor driving fixed pump and servo solenoid valve. They designed a fuzzy-PID controller for the packing pressure of the injection process based on the established model for the used system. They claimed that MATLAB results showed the efficiency of the proposed controller in reducing the error of the packing pressure tracking, good robust and more stable control system compared with a conventional PID controller [8]. Reiter, Stemmler, Hopmann, Ressmann and Abel, 2014 suggested an approach to control the cavity pressure of an injection molding machine using a model predictive controller based on a grey box model. They compared the performance of the resulting control system with that using a PI-controller [9]. Froehlich, Kemmetmuller and Kugi, 2018 presented a computationally efficient and scalable model of the injection process for servo-pump driven injection molding machines. The proposed model served as the basis for a model-based control strategy. Results confirmed the high model accuracy over the whole operating range for different mold geometries [10].

Gim and Rhee, 2021 presented an analysis methodology of cavity pressure profiles in injection molding machines using interpretation of machine learning model. They used the molding conditions: injection speed from 30 to 70 mm/s, packing pressure from 800 to 1200 bar and packing time from 2 to 5 seconds. They presented the molded part weight variation with injection speed, packing pressure and packing time [11]. Vukovic, Stemmler, Hornberg, Abel and Hopmann, 2022 investigated the use of an adaptive model-based predictive control for cross-phase cavity pressure control in injection molding. They used a Kalman filter to estimate the optimal state in a least-square sense of a time discrete nonlinear dynamic system. They applied piece-wise linearization for the model-based predictive control scheme, prediction, optimization and experimental results [12]. Liou et al., 2023 optimized the injection molding parameters based on the pressure profile characteristics, defined the standard quality characteristics through the optimized process parameters and combined it with the adaptive process control system proposed to maintain high quality production from the molding machine [13]. Kariminejad, Tomey and McAfee, 2024 outlined that the pressure profile during injection and packing phases has direct impact on the product quality. They proposed a model-based controller for the injection and cavity pressure during the molding cycle. The pressure profile was defined as the target trajectory in the proposed controller. They presented a step time response for a 400 bar desired cavity pressure without any overshoot with a settling time of about 5 seconds [14].

Nomenclature

C(s)	Laplace transform of the control system output
D(s)	Laplace transform of the disturbance input of the control system
$G_c(s)$	Controller transfer function
$G_p(s)$	Process transfer function
$G_{PDPI}(s)$	Transfer function of the PD-PI controller
I-PD	Integral-proportional derivative controller
I-P	Integral-proportional compensator
K	Process gain
K_d	Derivative gain parameter
K_i	Integral gain parameter
K_{pc}	Proportional gain parameter
PD-PI	Proportional Derivative – Proportional Integral controller
PID	Proportional Integral Derivative controller
R(s)	Laplace transform of the reference input of the control system
s	Laplace operator
T	Process time constant
T_d	Process delay time
2DOF	Two Degree of Freedom controller

2. Controlled Cavity Gate Pressure

Kamal et al. (1987) derived dynamic models for the cavity gate pressure of an injection molding machine processing a high density polyethylene according to the range of the valve opening of the machine hydraulics [4]. The model of the cavity gate pressure was a delayed first-order one having the form [4]:

$$G_p(s) = Ke^{-Tds}/(Ts+1) \tag{1}$$

Where: K = process gain (N/m^2)/% valve opening.

T = process time constant, s.

T_d = process delay (dead) time, s.

With 30 to 50 % valve opening, the authors gave the model parameters as:

$K = 12134.8\ N/m^2$ (1.76 psi) / % valve opening.

T = 0.11 s (2)

T_d = 0.01 s

To simplify the automatic control analysis of the control system with a delayed process, the exponential term in Eq.1 is replaced by a second-degree rational approximation using Pade-polynomial approximation [15]. The resulting process transfer function with the parameters in Eq.2 is:

$$G_p(s) = (1.213s^2-728.1s+1.456x10^5) / (1.1x10^{-5}s^3+0.0067s^2+1.38s+12) \qquad (3)$$

The step time response of this cavity gate pressure process reveals the dynamic characteristics of this process without any control. Its unit step time response is generated by the MATLAB command step [16] and shown in Fig.1.

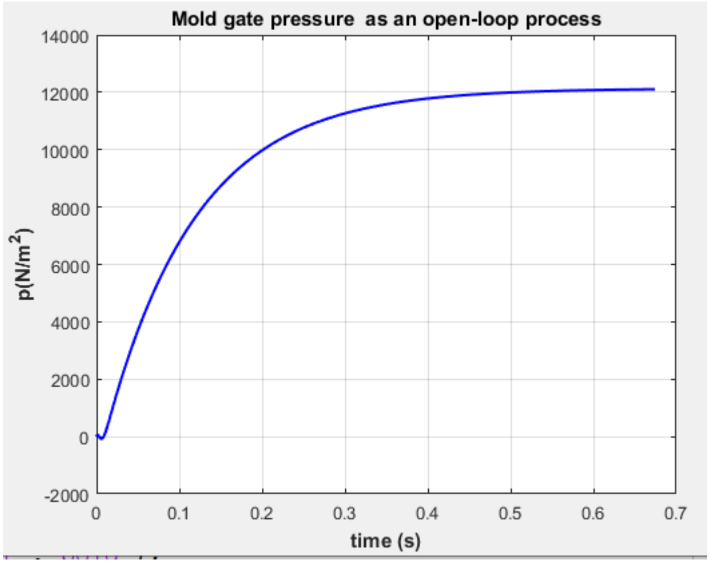

Fig.1 Unit step time response of the cavity gate pressure.

Comments:

- The cavity gate pressure process is stable.
- It shows little undershoot due to the process delay time.
- It has no overshoot.
- It has – 0.012 MN/m^2 steady-state error.
- It has a settling time of 0.428 s.
- Any good proposed control system has to overcome the large steady-state error.

3. Controlling the Cavity Gate Pressure using an I-PD Controller

The I-PD controller was introduced by the author in 2014 as one of the controllers of the second generation of the PID controllers. The author tested the performance of the I-PD controller through its use in controlling a highly oscillating second-order process [17], delayed double integrating process [18], third-order process [19], liquefied natural gas tank level [20] and furnace temperature control [21].

The block diagram of a control system incorporating an I-PD controller and the cavity gate pressure process is shown in Fig.2 [19, 22].

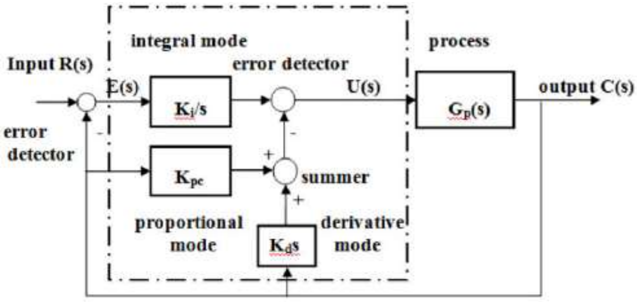

Fig.2 Cavity gate pressure control using I-PD controller [19].

- The transfer function of the control system for reference input tracking [C(s)/R(s)] is obtained using the block diagram in Fig.2 and Eq.3 for the process transfer function $G_p(s)$.

- The I-PD controller gain parameters are:

K_i = integral gain of the I-control mode.

K_{pc} = proportional gain of the P-control mode.

K_d = derivative gain of the D-control mode.

- The three controller gain parameters have to be tuned to optimize the performance of the control system.

The three I-PD controller parameters are tuned using the transfer function of the closed loop control system in Fig.2 and the MATLAB optimization toolbox [23] to minimize an ITAE performance index [24].

- The tuned I-PD controller parameters are:

$K_i = 7.478802$; $K_{pc} = 0.000107$

$K_d = 0.009760$ (4)

- The unit step time responses of the cavity gate pressure for reference and disturbance inputs are plotted using the transfer functions derived from the block diagram in Fig.2 and the tuned controller parameters in Eq.4 using the MATLAB command '*plot*' and shown in Fig.3.

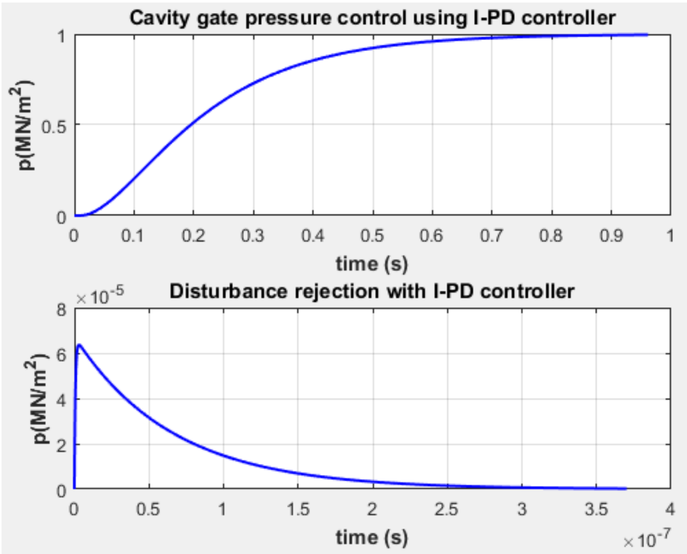

Fig.3 Cavity gate pressure control using an I-PD controller.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: 0.705 s
  - Steady-state error: zero
- For a disturbance input:
  - Maximum time response: 6.35×10^{-5} MN/m^2
  - Minimum time response: zero
  - Settling time to zero: 0.3 μs
- The I-PD controller succeeded to eliminate completely the maximum overshoot and steady-state error of the controlled cavity gate pressure.

4. Controlling the Cavity Gate Pressure 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: first-order delayed process [25], highly oscillating second-order process [26], integrating plus time delay process [27], delayed double integrating process [28], third-order process [29], internal humidity of a greenhouse [30], boost-guide rocket [31], electro-hydraulic drive [32], rolling strip thickness [33], furnace temperature [21], injection molding mold temperature [34] and injection molding barrel temperature [35].

- 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 [30]:

$G_{PDPI}(s) = [K_d K_{pc2} s^2 + (K_{pc1} K_{pc2} + K_d K_i)s + K_{pc1} K_i]/s$ (5)

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 four PD-PI controller parameters are tuned using the transfer function of the control system as derived from its block diagram and the MATLAB optimization toolbox [23] is used to minimize the ITAE performance index [24].
- The tuned PD-PI controller parameters are:

$K_{pc1} = 0.099000$; $K_d = 1.990000$

$K_{pc2} = 0.199000$; $K_i = 698600$ (6)

- The unit step time responses of the mold gate pressure for reference and disturbance inputs using the PD-PI controller are plotted using the MATLAB command '*plot*' [16] and shown in Fig.4.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: 1 µs
  - Steady-state error: zero
- For a disturbance input (to improve the performance of the control system regarding the rejection of the disturbance using a high pass second-order filter added after D(s):
  - Maximum step time response: 3.46×10^{-5} MN/m^2
  - Minimum time response: 6.00×10^{-7} MN/m^2
  - Settling time to zero: 2.5 µs

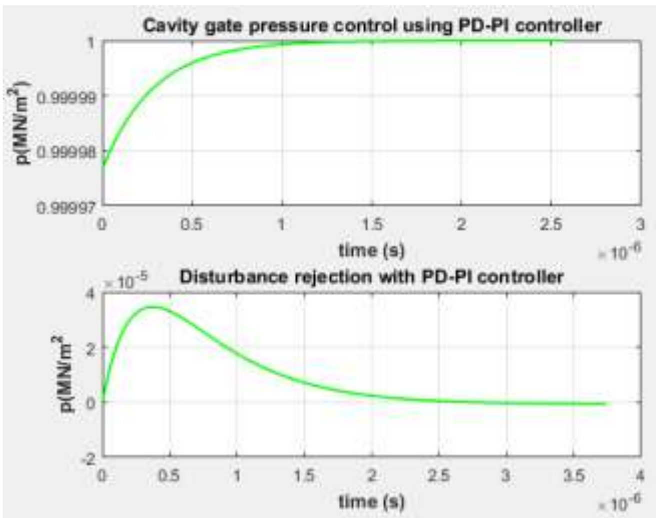

Fig.4 Cavity gate pressure control using a PD-PI controller.

5. Controlling the Cavity Gate Pressure using a 2DOF-2 Controller

Several 2DOF controllers were introduced by the author as members of the second generation of PID controllers introduced by him starting from 2014 to overcome the problems associated with the use of the conventional PID controller. The author used 2DOF controllers to control a number of processes having bad dynamics such as: highly oscillating second-order process [36], delayed double integrating process [37], gas turbine speed control [38], boost-glide rocket control [31], greenhouse temperature [39], liquefied natural gas tank level control [20], furnace temperature [21], electro-hydraulic drive [32], rolling strip thickness [33], injection molding mold temperature [34] and injection molding barrel temperature [35]. The structure of the 2DOF-2 controller used to control the cavity gate pressure is shown in Fig. 5 [35]. It comprises two sub-controllers: PID-control mode in the feedforward path receiving the error signal and a PD-control mode in a feedforward loop receiving the reference input of the control system as an input to this sub-controller mode. The transfer functions of the two control modes are as follows:

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

$G_{c2}(s) = (K_d s^2+K_{pc2}s+K_i)/s$ (7)

Where: K_{pc1} and K_i are the proportional and integral gains of the PI-mode of the 2DOF controller

K_{pc2} and K_d are the proportional, derivative gains of the PID-mode. The integral gain K_i is common in both PI and PID control modes of the 2DOF-2 controller.

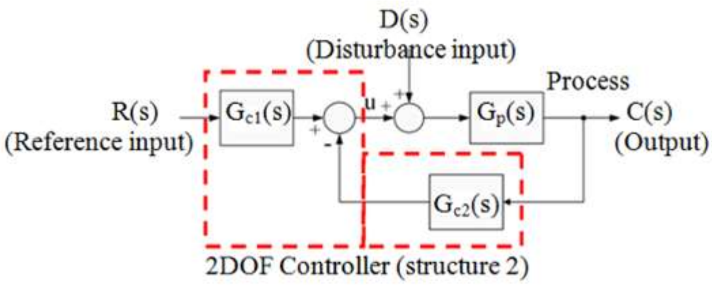

Fig. 5 Control system of cavity gate pressure control using a 2DOF-2 controller.

The transfer functions of the closed-loop control system for both reference and disturbance inputs using the 2DOF controller are derived from the block diagram in Fig.5.

- The 2DOF-2 controller structure proposed in the present work has four gain parameters to be tuned to provide accepted performance for the control system for both reference input tracking and disturbance rejection.
- The four 2DOF-2 controller parameters are tuned using the transfer function of the control system for reference input tracking and the MATLAB optimization toolbox [23] to minimize the ITAE performance index [24].
- The tuned 2DOF controller parameters are:

K_{pc1} = 0.048129 ; K_i = 798635

K_{pc2} = 3251.2 ; K_d = 3.9600 (8)

- The unit step time responses of the cavity gate pressure for reference and disturbance inputs using the 2DOF-2 controller are plotted using the transfer functions of the control system for both reference and disturbance inputs, the tuned controller parameters in Eq.8 and the MATLAB command '*plot*' [16] and shown in Fig.6.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: 10.8 ms
  - Steady-state error: zero
- For a disturbance input [to improve the performance of the control system regarding the rejection of the disturbance, a high pass second-order filter is added after D(s)]:
  - Maximum time response: 1.214×10^{-5} MN/m^2

- Minimum time response: -4.200×10^{-7} MN/m^2
- Settling time to zero: 0.2 ms

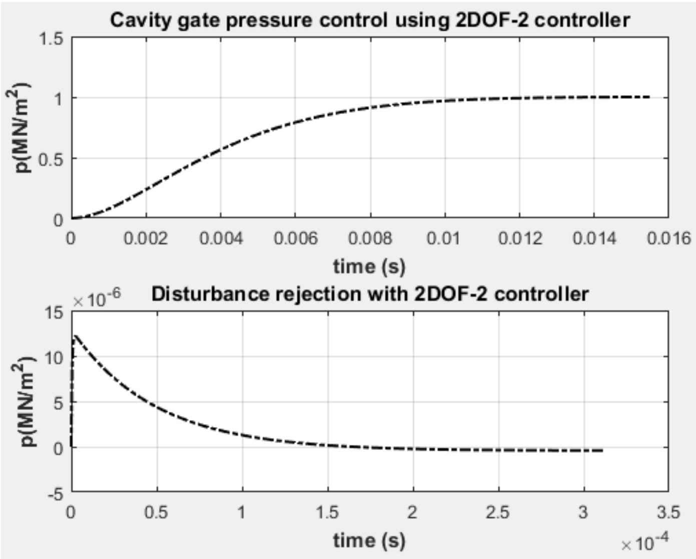

Fig.6 Cavity gate pressure control using a 2DOF-2 controller.

6.Controlling the Cavity Gate Pressure using an I-P Compensator

I-P compensator was introduced by the author in 2024 as one of the second generation of control compensators suggested to replace the first generation of such compensators for better control system performance. The author proposed the I-P compensator to control the strip thickness of a cold rolling mill [40]. The structure of the I-P compensator is shown in Fig.7 [40].

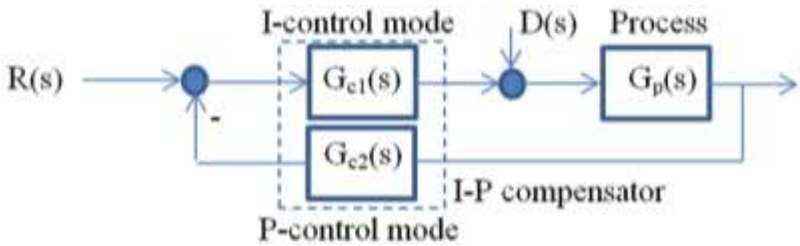

Fig.7 Cavity gate pressure control using I-P compensator [40].

The I-P compensator is composed of an integral control mode of $G_{c1}(s)$ transfer function in the forward path and a proportional control mode of $G_{c2}(s)$ transfer function in the feedback path. $G_{c1}(s)$ and $G_{c2}(s)$ are given by:

$G_{c1}(s) = K_i/s$, $G_{c2}(s) = K_{pc}$ (9)

Where: K_i = integral gain of the I-P compensator.

K_{pc} = proportional gain of the I-P compensator.

The I-P compensator has two gain parameters to be tuned to achieve stability and good performance. It is tuned as follows:

- The transfer function of the closed-loop control system in Fig.6 for reference input tracking is derived with the help of the block diagram and the process and compensator equation in Eqs.3 and 9.
- The ITAE performance index is chosen as a performance index [24].
- Investigating the closed-loop transfer function of the control system for reference input tracking reveals important characteristics for the resulting control system for the cavity gate pressure control. That is a zero steady-state error is possible if the I-P compensator has a unit proportional gain (K_{pc} = 1).
- This reduced the tuning process of the I-P compensator to the adjustment of only one gain parameter which is the integral gain K_i.
- The performance index is minimized in terms of the compensator parameter K_i using the MATLAB optimization technique [23].

- The tuned I-P compensator parameters are:

$K_i = 0.000331$, $K_{pc} = 1$ (10)

- The step time response of the control system for both reference input tracking and disturbance input using the I-P compensator is shown in Fig.8.

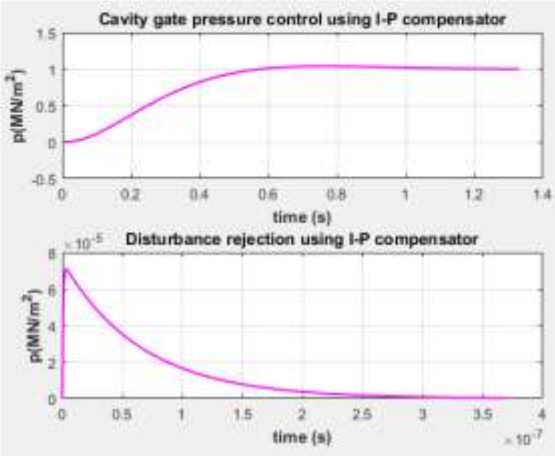

Fig.8 Cavity gate pressure control using an I-P compensator.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: 3.79 %
  - Settling time: 0.985 s
  - Steady-state error: zero
- For a disturbance input:
  - Maximum time response: 7.08×10^{-5} MN/m²
  - Minimum time response: zero
  - Settling time to zero: 0.35 µs

7. Comparison with Other Controllers

The performance of the control system used for the cavity gate pressure control is compared graphically and numerically when using the proposed controllers/compensator and a PID controller [4]. A graphical comparison of the performance of the control system with the five controllers/compensator is shown in Fig. 9 for the reference input of the control system. The effectiveness of the proposed four controllers/compensator for disturbance rejection is measured by the comparison graphs in Fig.10.

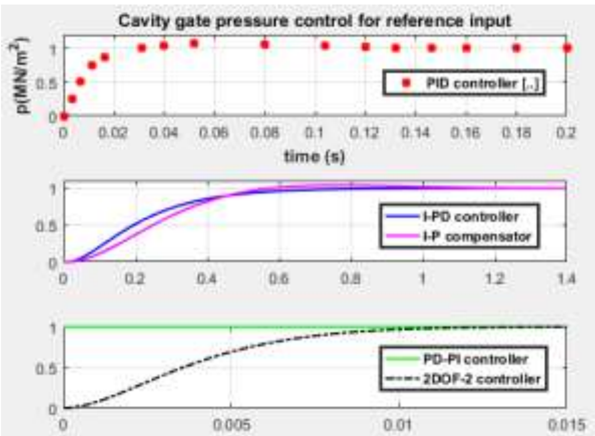

Fig. 9 Comparison of reference input step time response using five controllers.

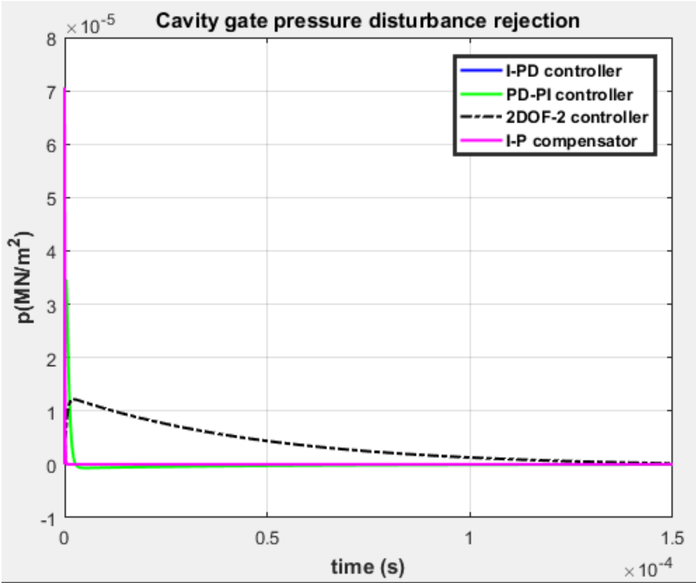

Fig. 10 Comparison of the disturbance rejection using four controllers /compensator.

A quantitative comparison for the time-based characteristics of the cavity gate pressure control system is shown in Table 1 for reference input of the control system.

Table 1 – Comparison of time-based characteristics for reference input.

Controller/compensator	Maximum overshoot (%)	Settling time (s)
PID controller [4]	7.46	0.110
I-PD controller	0	0.705
PD-PI controller	0	1×10^{-6}
2DOF-2 controller	0	0.0108
I-P compensator	3.79	0.985

The time-based characteristics of the disturbance step time response (disturbance rejection) are compared in Table 2.

Table 2 – Comparison of time-based characteristics for disturbance input (disturbance rejection).

Controller/compensator	Maximum time response (MN/m^2)	Minimum time response (MN/m^2)	Settling time to zero (µs)
I-PD controller	6.35×10^{-5}	0	0.30
PD-PI controller	3.46×10^{-5}	6.0×10^{-7}	2.50
2DOF-2 controller	1.214×10^{-5}	-4.2×10^{-7}	200
I-P compensator	7.08×10^{-5}	0	0.35

8. Conclusions

- The paper investigated the control of the cavity gate pressure using three controllers and one compensator from the second generation of controllers and compensators introduced by the author since 2014.
- The controllers proposed for this purpose was the I-PD, PD-PI and 2DOF (from the second generation of PID controllers) and the I-P compensator (from the second generation of control compensators).
- The four controllers/compensator were tuned using the MATLAB optimization toolbox and an ITAE error-based performance index.
- The performance of the control system was evaluated through the maximum percentage overshoot and the settling time for reference input tracking.
- For the disturbance input, the control system was evaluated through the maximum step time response, minimum step time response and settling time to zero.

- The four proposed controllers/compensator were compared with a PID controller from previous research work used to control the same process (cavity gate pressure).
- The controlled cavity gate pressure as a process to be controlled had bad dynamics when excited by a step input in terms of a large steady-state error (-0.012 MN/m^2).
- The I-PD controller could eliminate completely the maximum overshoot of the control system (compared with 7.46 % with the PID controller from the first generation).
- The PD-PI controller could eliminate completely the maximum overshoot and settling time (very small). This means that the step time response of the simulated control system for the cavity gate pressure was an ideal one (having step characteristics).
- The 2DOF controller could generate a reference input tracking unit step response without overshoot (compared with 7.46 % with the PID controller) and a settling time of 0.0108 s (compared with 0.11 s for the PID controller).
- The I-P compensator succeeded to reduce the maximum overshoot to 3.79 % (compared with 7.46 % with the PID controller).
- Regarding reference input tracking, the PD-PI controller is the best choice for the control engineer when controlling the cavity gate pressure of the thermoplastics molding machine.
- Regarding disturbance rejection, all the proposed controllers/compensator provided very small maximum and minimum step time responses settled to zero in less than 200 µs.
- Furthermore, if the interest of the control engineer is in the maximum time response due to disturbance input, then the 2DOF-2 controller is the best choice.
- If the interest of the control engineer is in the settling time to zero due to disturbance input, then the I-PD controller is the best choice.

References

1. Hassaan, G. A. (2024). Thermoplastics molding machine control, Part I: Mold temperature control using I-PD, PD-PI and 2DOF-2 controllers compared with a PID controller. *World Journal of Engineering Research and Technology,10, 5, 147-164.*
2. Hassaan, G. A. (2024). Thermoplastics molding machine control, Part II: Barrel temperature control using PD-PI, PI-PD and 2DOF-2 controllers compared with ANN-PI controller. *International Journal of Engineering and Techniques,10, 3, 6-15.*
3. Abu-Fara, D., Kamal, M. and Patterson, W. (1985). Evaluation of simple dynamic models and controllers for hydraulic and nozzle pressure in injection molding. *Polymer Engineering and Science, 25, 11, 714-723.*
4. Kamal, M., Patterson, W., Conley, N., Abu-Fara, D. and Lohfink, G. (1987). Dynamics and control of pressure in the injection molding of thermoplastics. *Polymer Engineering and Science, 27, 18, 1403-1410.*
5. Rafizadeh, M. (1996). Physically based dynamic model for the control of cavity pressure in thermoplastics injection molding. *Ph. D. Thesis, Department of Chemical Engineering, McGill University, Canada.*
6. Villalobos, A. C. (2001). Modeling and self-tuning pressure control in an injection molding cavity. *Revista Tecnica de la Facultad de Ingenieria Universidad del Zulia, 24, 1, 3-12.*
7. Huang, M. S. (2007). Cavity pressure based grey prediction of the filling-to-packing switchover point for injection molding. *Journal of Material processing Technology, 183, 2-7, 419-424.*
8. Wang, S., Ying, J., Chen, Z. and Feng, Y. (2010). Packing pressure control for energy-saving servo injection molding based on fuzzy-PID controller. *IEEE 2nd International Conference on Mechanical and Electronics Engineering, 1-3 August.*
9. Reiter, M., Stemmler, S., Hopmann, C., Ressmann, A. and Abel, D. (2014). Model predictive control of cavity pressure in an injection molding process. *Proceedings of the 19th World Congress, IFAC, Cape Town, South Africa, August 24-29, 4358-4363.*
10. Froehlich, C., Kemmetmuller, W. and Kugi, A. (2018). Control-oriented modeling of servo-pump driven injection molding machines in the filling and packing phase. *Mathematical and Computer Modeling of Dynamical Systems, 24,5, 451-474*
11. Gim, J. and Rhee, B (2021). Novel analysis methodology of cavity pressure profiles in injection molding machine processes using interpretation of machine learning model. *Polymers, 13, 3297, 18 pages.*
12. Vukovic, M., Stemmler, S., Hornberg, K., Abel, D. and Hoppmann, C. (2022). Adaptive model-based predictive control for cross-phase control in injection molding. *Journal of manufacturing Processes, 77, 730-742.*
13. Liou, G. et al. (2023). Optimize injection molding process parameters and build an adaptive process control system based on nozzle pressure profile and clamping force. *Polymers, 15, 610, 29 pages.*

14. Kariminejad, M., Tormey, D. and McAfee, M. (2024). Model-based pressure tracking using a feedback linearization technique in thermoplastic injection molding. *ArXiv: 2403 04388, V1, 5 pages.*
15. Hanta, V & Prochazka, A. (2009). Rational approximation of time delay. *Technika, 5, 166, 28-34.*
16. Mathworks (2024). Step response of dynamic system. https://www.mathworks.com/help/ident/ref/dynamicsystem.step.html
17. Hassaan, G. A. (2014). Tuning of an I-PD controller used with a highly oscillating second-order process. *International Journal of Mechanical Engineering and Technology, 5, 5, 115-121.*
18. G. A. Hassaan, G. A. (2015). Controller tuning for disturbance rejection associated with delayed double integrating processes, Part II: I-PD controller. *International Journal of Science and Engineering, 1, 3, 1-8.*
19. Mohamed, M. R. and Hassaan, G. A. (2020). Tuning of an I-PD controller for use with a third-order oscillating process. *International Journal of Computer Techniques, 7, 4, 1-6.*
20. Hassaan, G. A. (2024). Liquefied natural gas tank level control using PD-PI, I-PD and 2DOF controllers compared with PID control. *World Journal of Engineering Research and Technology*, 10, 1, 13-24.
21. Hassaan, G. A. (2024). Furnace control using I-PD, PD-PI and 2DOF controllers compared with fuzzy-neural controller. *International Journal of Computer Techniques, 11, 2, 1-10.*
22. Shiota, T. and Ohmari, H. (2013). Design of adaptive I-PD control system with variable reference model, *IEEE Automation Control Conference, 115-120.*
23. Messac, A. (2015) . *Optimization in practice with MATLAB for engineering students and professionals*. Cambridge University Press.
24. Martins, F. G. (2005). Tuning PID controllers using the ITAE criterion. *International Journal of Engineering Education, 21, 5, 867-873.*
25. Hassaan, G. A. (2014). Tuning of PD-PI controller used with first order delayed processes. *International Journal of Engineering Research and Technology*, Vol.3, Issue 4: pp.51-55.
26. Hassaan, G. A. (2014). Tuning of PD-PI controller used with a highly oscillating process. *International Journal of Science and Technology Research*, Vol.3, Issue 7: pp.145-147.
27. Hassaan, G. A. (2014).Tuning of PD-PI controller used with an integrating plus time delay process. *ibid , Vol.3, Issue 9: pp.309-313*.
28. Hassaan, G. A. (2015). Controller tuning for disturbance rejection associated with delayed double integrating process, Part I: PD-PI controller. *International Journal of Computer Techniques, 2, 3,110-115.*
29. Hassaan, G. A. (2020). Tuning of PD-PI controller used with a third order process. *International Journal of Application or Innovation in Engineering Management, 9, 8, 6-12*.
30. Hassaan, G. A. (2023). Tuning PD-PI and PI-PD controllers to control the internal humidity of a greenhouse. *International Journal of Engineering and Techniques, 9, 4, 1-9.*
31. Hassaan, G. A. (2023). Control of a boost-glide rocket using PD-PI, PI-PD and 2DOF controllers. *International Journal of Research Publication and Reviews, 4, 11, 917-923.*
32. Hassaan, G. A. (2024). Control of an electro-hydraulic drive using PD-PI, PI-PD and 2DOF-2 controllers compared with PID controller. *International Journal of Engineering and Techniques, 10, 2, 10 pages.*
33. Hassaan, G. A. (2024). Rolling strip thickness control using PD-PI, PI-PD and 2DOF-2 controllers compared with single model adaptive Smith predictor. *International Journal of Computer Techniques, 11, 2, 10 pages.*
34. Hassaan, G. A. (2024). Thermoplastics injection molding machine control, part I: Mold temperature control using I-PD, PD-PI and 2DOF-2 controllers compared with a PID controller. *World Journal of Engineering Research and Technology, 10, 5, 147-164.*
35. Hassaan, G. A. (2024). Thermoplastics injection molding machine control, part II: Barrel temperature control using PD-PI, PI-PD and 2DOF-2 controllers compared with ANN-PI controller. *International Journal of Engineering and Techniques, 10, 3, 6-15.*
36. Hassaan, G. A. (2015). Tuning of a 2DOF controller for use with a highly oscillating second-order-like process. *International Journal of Modern Trends in Engineering and Research, 2, 8, 292-298.*
37. Hassaan, G. A. (2015). Controller tuning for disturbance rejection associated with delayed double integrating process, Part V: 2DOF controller. *International Journal of Engineering and Techniques, 1, 4, 26-31.*
38. Hassaan, G. A. (2022). Tuning of 2DOF controllers for the speed control of a gas turbine. *International Journal of Engineering and Techniques, 8, 2, 35-44.*

39. Hassaan, G. A. (2023). Temperature control of a greenhouse using PD-PI, PI-PD and 2DOF controllers. *International Journal of Engineering Inventions, 12, 9, 156-162.*

40. Hassaan, G. A. (2024). Rolling strip thickness control using I-P, I-PD, PD-PI and PI-first order compensators compared with an adaptive PI controller. *World Journal of Engineering Research and Technology, 10, 4, 50-64.*

DEDICATION

Alamal-Alsharif Plastics:

- I dedicate this work to one of the biggest plastics production companies in Egypt: Alamal-Alsharif Plastics.
- It started in 1964 as **Alsharif Plastics** and after few years of excellence, it was called **Alamal-Alsharif Plastics.**
- I have visited them during early 1980's and felt how great they were from their machinery and administration.
- They had three factories in 2019 housing 93 extrusion and injection molding machines.
- Its annual production is 60,000 tons of plastic pipes and 12,000 tons of plastic fittings.
- The company is following the latest modern German technology in plastics manufacturing.
- They produce piping systems for drinking water supply, sewage networks, electricity and telephone piping and agricultural drainage systems..
- It was exporting its products since 2002 to Iraq,Yeman, Libya and Tunisia.
- The company (now) is owned to Egyptian individuals (51.1 %), foreign individuals (2.31 %) and Egyptian governmental banks (46.59 %).
- The Egyptian government decided to offer a share of the company within its IPD program (list of 35 state owned companies).
- Because you were great and still great I dedicate this research work to you as a great plastic production company after the National Plastics Company.

BIOGRAPHY

GALAL ALI HASSAAN:

- Emeritus Professor of System Dynamics and Automatic control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974 respectively.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, Egypt.
- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 320 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Member of the Editorial Board of a number of international journals.
- Reviewer in some international journals.