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THERMOPLASTICS INJECTION MOLDING MACHINE CONTROL, PART IV: MOLD PACKING PRESSURE CONTROL USING I-PD, PD-PI, PI-PD AND 2DOF-2 CONTROLLERS COMPARED WITH AN ADAPTIVE IMC CONTROLLER

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ABSTRACT

The control of cavity packing pressure in injection molding machines is essential to maintain production of molded plastic parts with good quality and minimum defects. The paper presents the control of the cavity packing pressure phase using four controllers from the second generation of PID controllers (I-PD, PD-PI, PI-PD and 2DOF-2). A proper tuning technique is selected to tune the proposed controllers using an ITAE performance index. The step time response of the control system using the four proposed controllers is presented and compared with using an adaptive IMC controller used to control the same process in a previous research work and the time-based characteristics are compared. The comparison reveals the best controller among the five controllers depending on a graphical and quantitative comparison study for both reference and disturbance inputs.

KEYWORDS: Injection mold packing pressure control, I-PD controller, PD-PI controller, PI-PD controller, 2DOF-2 controller, controller tuning.

INTRODUCTION

Too many parts are produced using injection molding machines. They are popular because they process thermoplastics having variety of properties and ease of production with large mass production. Product quality is an important aspect that has to be seriously considered by machine designers and control engineers. Mold cavity packing pressure is one of the key variables in controlling the quality of the injection molded product. This part of research series dealing with the control of the injection molding machine introduces some controllers from the second generation of PID controllers providing high performance of the control system and accurate control for better product quality. We start by taking an idea about some of the research work regarding cavity packing pressure modeling and control.

Rafizadeh (1996) studied the dynamic modeling and control of injection molding cavity pressure dealing with filling and packing phases. He derived a 6^{th} order model with piece-wise linearization for the cavity pressure during packing. He applied adaptive PI, PID and IMC controllers for the packing phase with experimental model validation using polyethylene and polystyrene.[1] Kazmer and Barkan (1997) described a scheme for the simultaneous control of cavity pressure at multiple locations in multi-gated parts or multi-cavity molds. They presented the development and capabilities of the proposed control in both filling and packing phases.[2] Zarate (1999) proposed two methods for the control of part weight in injection molding machines. This was achieved by controlling the temperature and pressure of the mold cavity. They employed a self-tuning algorithm with an observer for controlling the cavity pressure to compensate for melt temperature deviation measured in previous cycles.[3] Zheng and Alleyne (2000) designed and tested a learning control scheme with bumpless transfer between filling and packing phases of the injection molding machine. They described and tested a high gain bumpless transfer scheme. They claimed that their scheme resolved the problem of the fill-pack transition in injection molding machine control.[4]

Villalobos (2001) performed open-loop experiments to assign an appropriate model order for the cavity pressure of an injection molding machine. He employed a self-tuning algorithm with an observer to control the cavity pressure time profile to a set point trajectory. He determined the model parameters using he pole location procedure and implemented the self-tuning algorithm with a first-order observer and state feedback.[5] Chen and Gao (2003) studied the effect of different types of packing profiles on part weight, shrinkage, flash, thickness and evenness. They made recommendations for specific improvements of those quality aspects through a proper profile type selection.[6] Wang, Ying, Chen and Feng (2010) presented an energy saving design of servo injection molding system with servomotor driving fixed pump and servo solenoid valve. They designed a fuzzy-PID controller for the packing pressure in the mold. MATLAB simulation results showed that the used controller could reduce the error of the packing pressure tracking and provided robust and more stable control system than the conventional PID controller.[7]

Dewantoro and Feriyonika (2011) proposed a cavity pressure control scheme using model-reference adaptive control to deal with the time varying nature of the mold cavity pressure. Controller gains were adjusted using an MIT rule while a lead compensator was used to improve the transient response. They claimed that simulation illustrated the effectiveness of their approach during filling and packing phases.[8] Wang, Ying, Chen and Cai (2011) presented a grey PI controller for packing pressure control of an injection molding process. Their controller was designed to overcome large overshoot, large static error and long delay time. They integrated predictive grey system, robust fuzzy and PI control strategies. Experimental results showed that their proposed controller offered good performance in achieving the objectives of their design.[9] Tardif et al. (2012) outlined that improving the quality of the injection process required prediction of shrinkage, warpage, residual stress and pressure impact on morphology and the shape of the final injected product. They confirmed that crystallization was strongly coupled to flow history based on mold pressure analysis and experimental comparison.[10]

Xie et al. (2014) outlined that packing phase control during injection molding plays a crucial role in ensuring product quality. They proposed a part weight control based on cavity pressure temperature during the packing phase and concluded that their approach was effective for part weight control applied on polypropylene and ABS polymers.[11] Guo, Farotti and Natalini (2017) investigated the influence of of the injection molding parameters on the mechanical properties of polypropylene. They presented the cavity pressure in the mold during filling and packing phases. They analyzed the effect of melt temperature, mold temperature, packing pressure and cooling time on the mechanical properties of the molded piece.[12] Froehlich, Kermetmuller and Kugi (2018) presented a mathematical model for the injection molding machine for servo-pump driven machines. They combined the model with a phenomenological model describing the injection process and the proposed model was tailored to real time applications for the design of model-based control strategies. They concluded that a number of experiments confirmed the high accuracy of their model over the whole operating range for different mold geometries.[13]

Lin et al. (2019) proposed a servo-hydraulic system to simulate the filling and packing phases of an injection molding machine. They conducted experiments to evaluate the pressure control in the packing state. They claimed that their proposed system met the required performance standards when operated with PID controller. Maximum overshoot was in the range from 7.87 to 20 % depending on the injection velocity.[14] Froehlich, Kermetmuller and Kugi (2020) proposed a control system for an injection molding machine with servo-motor driven pump consisting of a Lyapunov-based load-volume flow estimator and a model-predictive controller based on Ricatti recursion. They claimed that their proposed control scheme featured high performance for the filling and packing phases without knowledge of the mold geometry or information from previous cycles and showed robustness with respect to model uncertainties.[15] Chen, Wu and Hwang (2021) designed an experimental system to study the control of the injection and packing phases of injection molding. They proposed and designed a self-tuning fuzzy PID controller for the time response of the packing pressure control.[16] Chang et al. (2022) established packing pressure setup technology to optimize the molded part quality and the production stability. They claimed that packing pressure control improved the product weight replication by 54 %, reduced total shrinkage by 83 % and improved warpage by 12 %.[17]

Chen et al. (2023) used response surface methodology to build a crystallization time prediction model verified by determining the warpage of molded parts at various cooling times. They varied the packing pressure, packing time and melt temperature to assign the correlation with part shrinkage.[18] Hassaan (2024) investigated the dynamic models derived for the mold-gate cavity pressure I a previous research work and their use of a PID controller to control the cavity-gate pressure. He proposed three controllers from the second generation of PID controllers and one compensator from the second generation of control compensators to control the same gate pressure process. He could eliminate completely the maximum percentage overshoot (compared with 7.6 % for the PID controller) and reduce the settling time to only one µs compared with 0.11 s for the PID controller).

Controlled Mold Packing Pressure

Rafizadeh derived a 6^{th} order model for the transfer function of the mold packing pressure and used adaptive PI, PID and IMC controllers to control the mold packing pressure.[1] The mathematical model he used for the cavity packing pressure is used her to support the proposal of four controllers from the second generation of PID controllers. The model has a transfer function with 1 ms time constant for the used servo-valve given by[1]

$$G_p(s) = 285714 / [(s^2+84.68s+59038)(s^2+83.44s+774.59)(s+0.46)] \qquad (1)$$

The unit step time response of cavity packing pressure having the dynamics defined by Eq.1 is shown in Fig.1 as generated by the '*step*' command of MATLAB.[20]

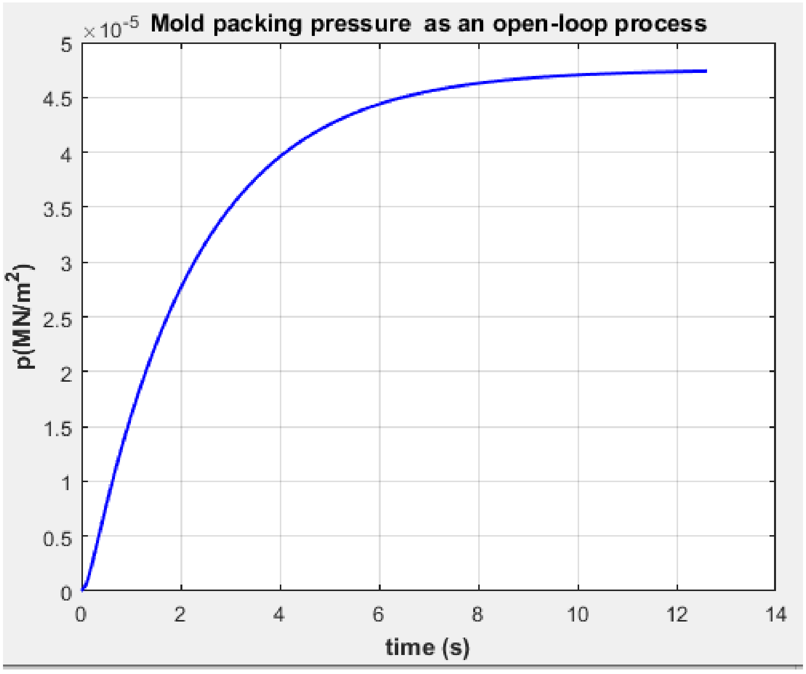

Figure 1: Step time response of the mold packing pressure as a process.

COMMENTS

- The mold-cavity packing pressure process is stable.
- It has a steady-state error of about a unit value for a unit step input of the servovalve percentage input.
- It has zero maximum percentage overshoot.
- It has a settling time of 8.3 s.
- It has zero maximum undershoot.

Controlling the Mold Cavity Packing Pressure Using an I-PD Controller

The I-PD controller is one of the second generation of PID controllers introduced by the author to replace the first generation of the PID controllers since 2014. The author proposed to use the I-PD controller to control a highly oscillating second-order process[21], delayed double integrating process[22], third-order process[23], liquefied natural gas tank level[24], furnace temperature control[25] and cavity gate pressure of an injection molding machine.[19]

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

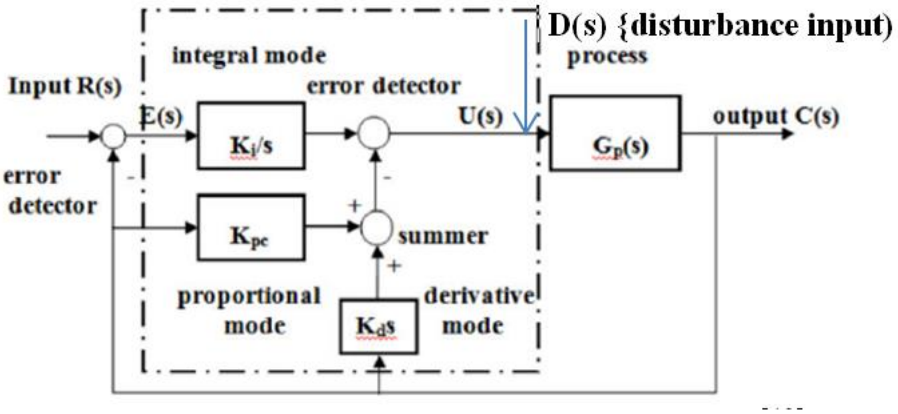

Figure 2: Structure of the I-PD controller.[19]

The I-PD controller has the transfer functions $G_I(s)$, $G_P(s)$ and $G_D(s)$ given by:

$G_I(s) = K_i/s$

$G_P(s) = K_{pc}$ (2)

and $G_D(s) = K_d\, s$

Where: K_i = integral gain of the integral control mode

K_{pc} = proportional gain of the proportional control mode

K_d = derivative gain of the derivative control mode

It has three gain parameters to be tuned for stable control system and for good performance in terms of the control system steady-state error, maximum overshoot and settling time.

- The gain parameters of the I-PD controller (K_i, K_{pc} and K_d) are tuned using the MATLAB optimization toolbox[26] and an ITAE performance index.[27] The tuned gain parameters of the I-PD controller are:

$K_i = 145.949493$, $K_{pc} = 40.018016$, $K_d = -688.528260$ (3)

- The unit step time response of the control system for the cavity packing pressure with reference and disturbance inputs using Eqs.1, 2 and 3 and the transfer functions derived from the block diagram in Fig.2 is shown in Fig.3.

- A second-order high pass filter is used with the disturbance input to improve the characteristics of the control system regarding the disturbance rejection.

COMMENTS

➢ The I-PD controller provided a reference input tracking step time response having the following characteristics:

- Maximum percentage overshoot: zero
- Settling time: 10.355 s

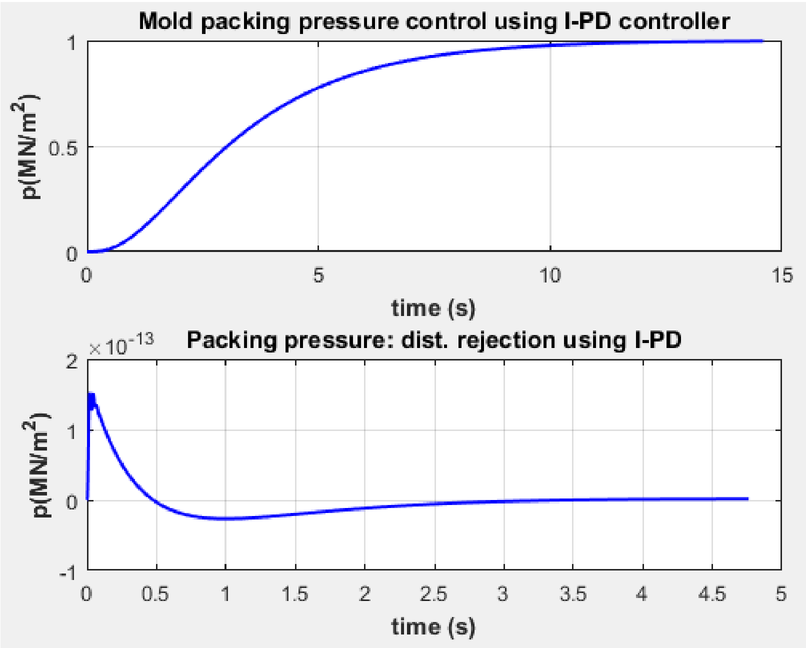

Figure 3: Cavity packing pressure controlled by an I-PD controller.

➢ The success of the I-PD controller to reject the disturbance input is measured by the following characteristics using second-order high pass filter in front of the disturbance variable D(s).

- Maximum cavity packing pressure step time response: 1.523 x 10^{-13} MN/m^2
- Minimum mold temperature step time response: -0.265 x 10^{-13} MN/m^2
- Settling time to zero (approximate): 3 s.

Controlling the Cavity Packing Pressure Using a PD-PI Controller

The PD-PI controller was introduced by the author to control a number of difficult processes since 2014 including: its use in controlling first-order delayed processes[30], highly oscillating second-order process[31], integrating plus time-delay process[32], delayed double integrating process[33], third-order process[34], boost-glide rocket engine[35], rocket pitch angle[36], LNG tank pressure[37], boiler temperature[38] boiler-drum water level[39], greenhouse internal humidity[40], coupled dual liquid tanks[41], BLDC motor [42], furnace temperature[25], electro-hydraulic drive[44], rolling strip thickness[45] and cavity gate pressure.[19] The PD-PI controller is composed of two elements: PD-control mode, $G_{c1}(s)$ in cascade with a second PI-control mode, $G_{c2}(s)$ just after the error detector.

The two elements have transfer functions given by:

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

and $G_{c2}(s) = K_{pc2} + K_i/s$ (4)

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 PD-PI controller has four gain parameters (K_{pc1}, K_d, K_{pc2} and K_i) to be tuned to satisfy the objectives of using the PD-PI controller to control the cavity packing pressure and provide good control system performance for reference and disturbance inputs.

- To control the cavity packing pressure for reference input tracking, the transfer function of the closed loop control system is derived using the block diagram and Eqs.1 and 4.

- The PD-PI controller is tuned using the same tuning procedure used with the I-PD controller.

- The tuned parameters of the PD-PI controller using an ITAE performance index [27] are as follows

$K_{pc1} = 0.999250$, $K_d = 1.683010$

$K_{pc2} = 3.919998$, $K_i = 32080.75$ (5)

- Using the closed-loop transfer function of the closed-loop control system for reference and disturbance inputs and the controller parameters in Eq.5, the unit step time response of the control system incorporating the PD-PI controller and the cavity packing pressure process shown in Fig.4.

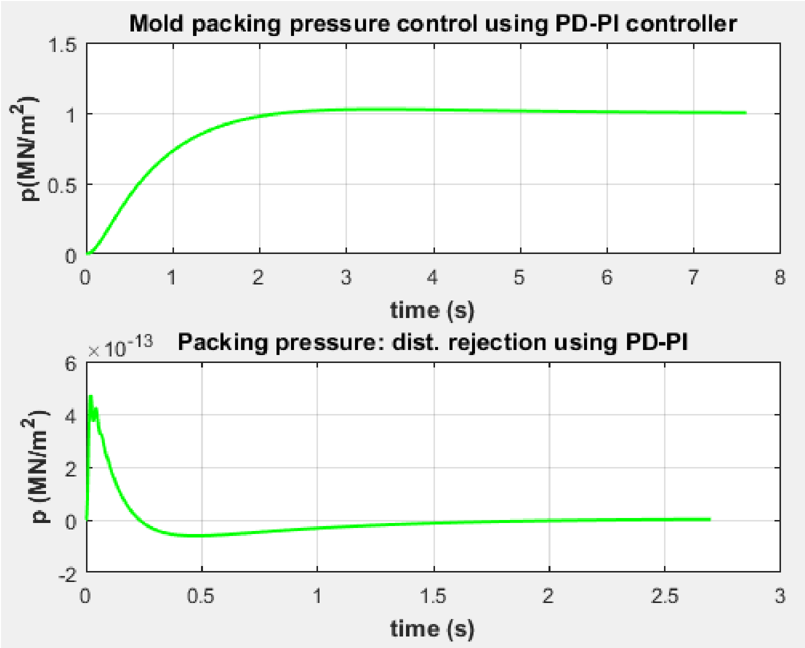

Figure 4: Cavity packing pressure controlled by a PD-PI controller.

COMMENTS

➢ The PD-PI controller provided a reference input tracking step time response having the following characteristics

- Maximum percentage overshoot: 2.717 %
- Settling time: 4.50 s.

➢ The success of the PD-PI controller to reject the disturbance input is measured by the following characteristics

- Maximum cavity packing pressure step time response: 4.71 x 10^{-13} MN/m^2
- Minimum mold temperature step time response: -0.61 x 10^{-13} MN/m^2
- Settling time to zero (approximate): 2.0 s.

Controlling the Cavity Packing Pressure using a PI-PD Controller

- The PI-PD controller was introduced by the author since 2014 as one of the second generation of PID controllers. He proposed a PI-PD controller to control: highly oscillating second-order process[47], third-order process[48], fourth-order blending process[49], boost-glide rocket engine[35], BLDC motor[42], boiler drum water level[39], electro-hydraulic drive[44], rolling strip thickness[45] and a barrel temperature control of an injection molding machine.[46]

- The block diagram of a control system incorporating a PI-PD controller controlling the boiler-drum water level is shown in Fig.3.[45]

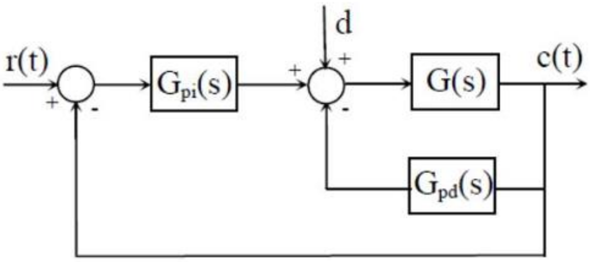

Figure 5: Block diagram of PI-PD controlled process.[45]

- 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

$G_{PI}(s) = K_{pc1} + (K_i/s)$; $G_{PD}(s) = K_{pc2} + K_d s$ (6)

- To control the cavity packing pressure for reference input tracking, the transfer function of the closed loop control system is derived using the block diagram in Fig.5 and Eqs.1 and 6.

- The PI-PD controller is tuned using the same tuning procedure used with the I-PD controller.

- The tuned parameters of the PI-PD controller using an ITAE performance index[27] are as follows

$K_{pc1} = 40.39549$, $K_i = 3760.9695$

$K_{pc2} = 43.63250$, $K_d = 3292.7109$ (7)

- Using the closed-loop transfer function of the closed-loop control system for reference and disturbance inputs and the controller parameters in Eq.7. The unit step time response of the control system incorporating the PI-PD controller and the cavity packing pressure process is shown in Fig.6.

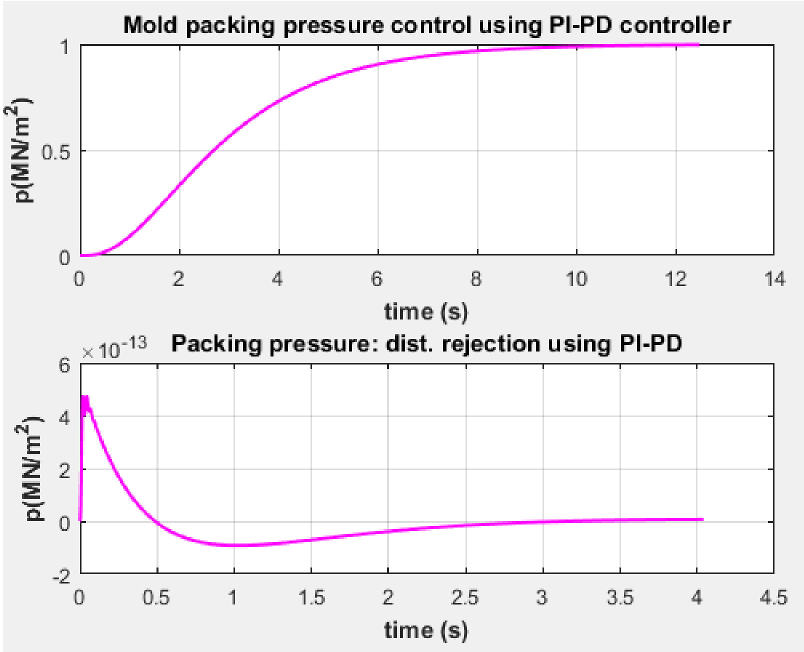

Figure 6: Cavity packing pressure controlled by a PI-PD controller.

COMMENTS

➢ The PI-PD controller provided a reference input tracking step time response having the following characteristics

- Maximum percentage overshoot: 2.470 %
- Settling time: 20.37 s.

➢ The success of the PI-PD controller to reject the disturbance input is measured by the following characteristics

- Maximum cavity packing pressure step time response: 4.710 x 10^{-13} MN/m^2
- Minimum mold temperature step time response: -0.164 x 10^{-13} MN/m^2
- Settling time to zero (approximate): 0.30 s.

Controlling the Cavity Packing Pressure using a 2DOF-2 Controller

The 2DOF-2 controller was introduced by the author to control a number of difficult processes since 2014 including: liquefied natural gas pressure[37], coupled dual liquid tanks[41], boost-glide rocket engine[35], BLDC motor control[42], highly oscillating second-order process[51], boiler drum water level[39], boiler temperature[38], electro-hydraulic drive[44], rolling strip thickness[45], furnace temperature[25], mold temperature[50], injection molding machine barrel temperature[46] and mold cavity pate pressure.[19]

The structure of the 2DOF controller used in the present work is shown in Fig.7.[52] The 2DOF-2 controller is composed of two control elements: reference input element receiving its input from the reference input of the control system which is a PI-control mode having $G_{ff}(s)$ transfer function and a feedback element receiving its input from the packing pressure signal which is a PID-control mode having $G_c(s)$ transfer function.

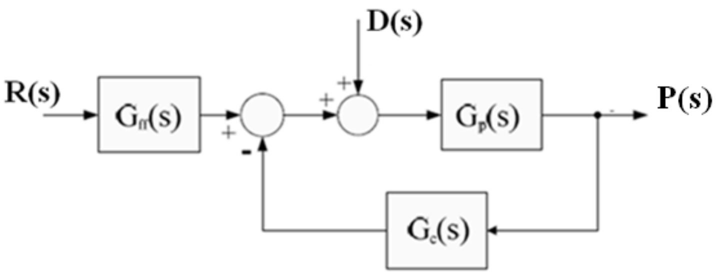

Figure 7: Cavity packing pressure control using a 2DOF-2 controller.[52]

The transfer functions of the 2DOF-2 controller are as follows:

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

and $G_c(s) = K_{pc2} + (K_i/s) + K_d s$ (8)

Where: K_{pc1} = proportional gain of the PI-control mode.

K_i = integral gain of the PI and PID-control modes.

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

K_d = derivative gain of the PID-control mode.

The 2DOF-2 controller has four gain parameters to be tuned to provide the required performance of the closed-loop system of the mold packing pressure control. The controller is tuned following the same procedure used with the I-PD controller. The tuned parameters of the 2DOF-2 controller are as follows

$K_{pc1} = 4.030810$, $K_i = 13533.7380$

$K_{pc2} = 5.987464$, $K_d = -39744.1058$ (9)

The closed loop transfer functions of the control system for both reference and disturbance inputs are derived from the block diagram in Fig.5 using the process transfer function in Eq.1 and the controller transfer functions in Eq.8 with the tuned controller parameters in Eq.9. The unit step time response of the control system is plotted using the step command of MATLAB and shown in Fig.8 for both inputs.

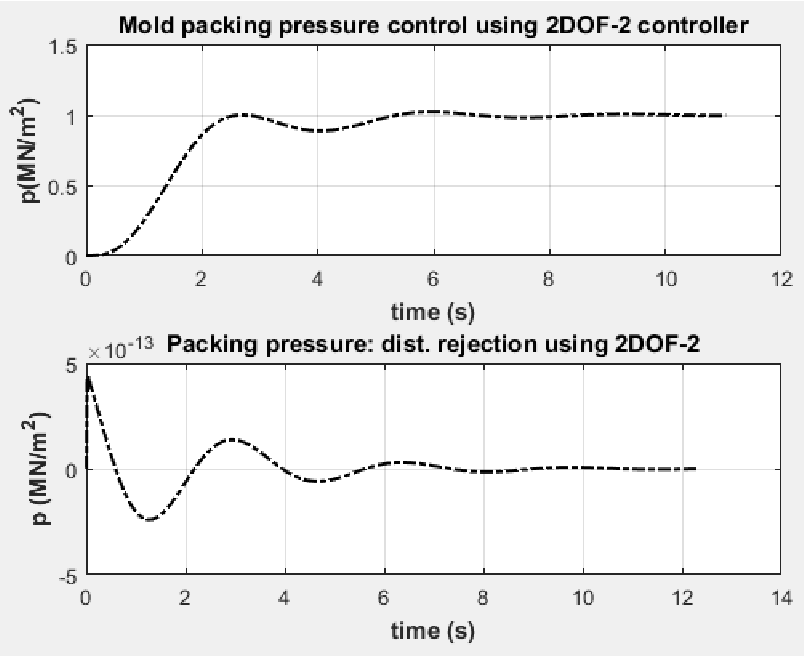

Figure 8: Cavity packing pressure controlled by a 2DOF-2 controller.

COMMENTS

➢ The 2DOF-2 controller provided a reference input tracking step time response having the following characteristics

- Maximum percentage overshoot: 2.186 %
- Settling time: 6.140 s.

➢ The success of the 2DOF-2 controller to reject the disturbance input is measured by the following characteristics

- Maximum packing pressure step time response: 4.40 x 10^{-13} MN/m^2
- Minimum packing pressure step time response: -2.40 x 10^{-13} MN/m^2
- Settling time to zero (approximate): 8.00 s.

Characteristics Comparison of the Proposed Controllers with an IMC controller

- The reference for the comparison of the performance of the proposed controllers is a tuned digital adaptive IMC controller used by Rafizadeh to control the same process.[1]

- The adaptive IMC controller proposed by Rafizadeh provided the time based characteristics

- Maximum percentage overshoot: 23.84 %.
- Settling time: 2.40 s.

- The characteristics comparison takes two forms: graphical and quantitative ones as follows

➢ For the reference input: *Graphical comparison*: The comparison of the tracking step time response of the packing pressure for the adaptive IMC, I-PD, PD-PI, PI-PD and 2DOF controllers is shown in Fig.9.

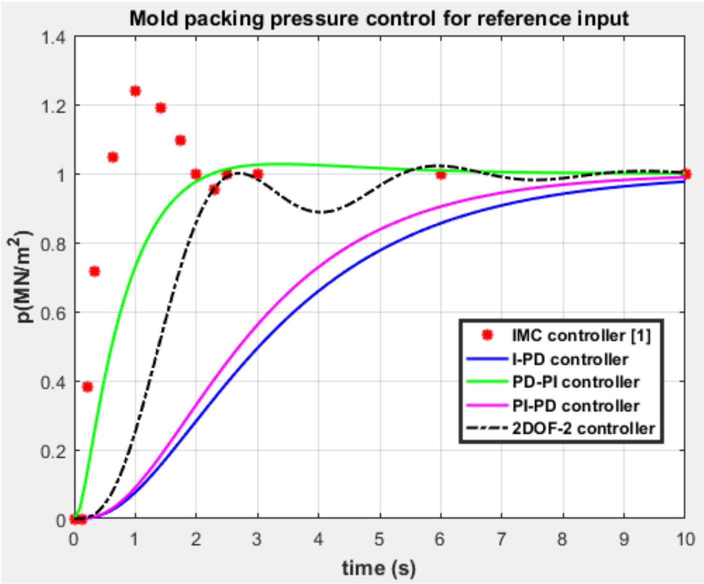

Figure 9: Comparison of reference input tracking step time responses.

➢ For the disturbance input: The comparison is presented in Fig.10 (without the adaptive IMC controller).

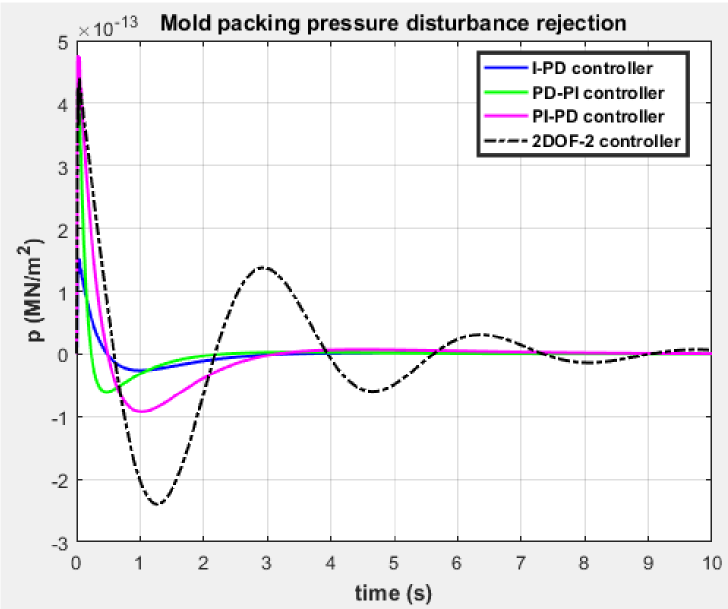

Figure 10: Comparison of disturbance input step time responses.

➢ *Quantitative comparison*: The time-based characteristics of the control system for the cavity packing pressure control are quantitatively compared in Table 1 for reference input tracking and Table 2 for disturbance input.

Table 1: **Reference input time-based characteristics of cavity packing pressure control using adaptive IMC controller, I-PD, PD-PI, PI-PD and 2DOF-2 controllers.**

Characteristics	Adaptive IMC controller	I-PD controller	PD-PI controller	PI-PD controller	2DOF-2 controller
Maximum overshoot (%)	23.84	0	.717	2.47	2.186
Settling time (s)	2.400	10.355	4.500	20.37	6.140

Table 2: **Disturbance input time-based characteristics comparison.**

Characteristics	I-PD controller	PD-PI controller	PI-PD controller	2DOF-2 controller
Maximum time response (MN/m^2)	1.523×10^{-13}	4.710×10^{-13}	4.710×10^{-13}	4.400×10^{-13}
Minimum time response (MN/m^2)	-0.265×10^{-13}	-0.610×10^{-13}	-0.164×10^{-13}	-2.400×10^{-13}
Settling time to zero, s (approximate)	3	2	0.3	8

CONCLUSION

- The objective of the paper was to investigate the use and tuning of I-PD, PD-PI, PI-PD and 2DOF controllers to control mold cavity packing pressure in injection molding machines.
- The four proposed controllers are from the second generation of PID controllers presented by the author since 2014.
- All the proposed controllers were tuned using the MATLAB optimization toolbox and an ITAE performance index.
- An adaptive IMC controller from previous work was compared with the four proposed controllers.

- The I-PD controller succeeded to eliminate completely the maximum overshoot of the control system compared with 23.84 % with the IMC controller and succeeded to settle after 10.35 s compared with 2.4 s for the IMC controller for reference input tracking.
- The PD-PI controller succeeded to reduce the maximum overshoot of the control system to 2.717 % compared with 23.84 % with the IMC controller and succeeded to settle after 4.5 s compared with 2.4 s for the IMC controller for reference input tracking.
- The PI-PD controller succeeded to reduce the maximum overshoot of the control system to 2.47 % compared with 23.84 % with the IMC controller and settles after 20.37 s compared with 2.4 s for the IMC controller for reference input tracking.
- The 2DOF-2 controller succeeded to reduce the maximum overshoot of the control system to 2.186 % compared with 23.84 % with the IMC controller and settles after 6.14 s compared with 2.4 s for the IMC controller for reference input tracking.
- The performance of the proposed controllers regarding disturbance rejection was excellent through the use of a high pass second-order filter receiving the disturbance input. Both maximum and minimum time responses had negligible values indicating the success of all the presented controllers to suppress the input disturbance.
- If the interest of the control engineer is to satisfy the condition of minimum maximum overshoot, then the proposed I-PD controller is the best choice.
- If the interest of the control engineer is to satisfy the condition of minimum settling time, then the adaptive IMC controller is the best choice.
- If the interest of the control engineer is to satisfy the condition of minimum settling time to zero during disturbance rejection, then the proposed PI-PD controller is the best choice.

REFERENCES

1 Rafizadeh, M., “Physically-based dynamic model for the control of cavity pressure in thermoplastics injection molding”, Ph. D. Thesis, Faculty of Graduate Studies, McGill University, Montreal, August, 1996.

2 Kazmer, D. and Barkan, P., “Multi-cavity pressure control in the filling and packing stages of the injection molding process”. Polymer Engineering and Science, 1997; 37(11): 1865-1879.

3 Kamal, M., Varela, A. and Patterson, W., “Control of part weight in injection molding of amorphous thermoplastics”, Polymer Engineering and Science, 1999; 99(5): 940-952.

4 Zheng, D. and Alleyne, A., "Learning control of an electro-hydraulic injection molding machine with smoothed fill-to-pack transition", Proceedings of the American Control Conference, Chicago, June, 2000; 2558-2562.

5 Villalobos, A. E., "Modeling and self-tuning pressure control in an injection molding cavity", Rev. Tec. Ing. Univ. Zulia, 2001; 24(1): 3-12.

6 Chen, X. and Gao, F., "A study of packing profile on injection molded part quality". Materials Science and Engineering, 2003; A358: 205-213.

7 Wang, S., Ying, J. Chen, Z. and Feng, Y., "Packing pressure control for energy saving servo injection molding machine based on fuzzy-PID controller", 2nd International Conference on Mechanical and Electronics Engineering, Kyoto, Japan, 1-3 August, 2010.

8 Dewantoro, G. and Feriyonika, F., "Model reference adaptive control of cavity pressure in injection mold during filling and packing phases", 2nd International Conference on Instrumentation, Control and Automation, Bandung, Indonesia, 15-17 November, 2011.

9 Wing, S. Ying. J., Chen, Z. and Cai, Y. "Grey fuzzy PI control for packing pressure during injection molding process", Journal of Mechanical Science and Technology, 2011; 25: 1061-1068.

10 Tardif, X. et al., "Determination of pressure in the molding cavity of injected semi-crystalline thermoplastics", Proceedings of the 11th Biennial Conference on Engineering Systems Design and Analysis, Nantes, France, June 2-4, 2012.

11 Xie, P. et al., "Study on packing phase control based on the cavity pressure-temperature during injection molding", Polymer Engineering Processing, 2014; 29(2): 184-190.

12 Farotti, E. and Natalini, M., "Injection molding: influence of process parameters on mechanical properties of polypropylene polymer. A first study", AIAS International Conference on Stress Analysis, Pisa, Italy, 6-9 September, 2017; 256-264.

13 Froehlich, C., Kermetmuller, W. and Kugi, A., "Control oriented modeling of servo-pump driven injection molding machines in the filling and packing phases", Mathematical and Computer Modeling of Dynamical Systems, 2018; 24(5): 451-474.

14 Lin, C. et al., "Injection molding process control of servo-hydraulic system", Applied Sciences, 2019; 10(71): 11.

15 Froehlich, C., Kermetmuller, W. and Kugi, A., "Model-predictive control pf servo-pump driven injection molding machine", IEEE Transactions on Control Systems Technology, 2020; 28(5): 1665-1680.

16 Chen, C., Wu, K. and Hwang, S., "Development of a servo-hydraulic system with self-tuning fuzzy PID controller to simulate injection molding process", Microsystem Technologies, 2021; 27(4): 1217-1238.

17 Chang, Y. et al. "The investigation of novel dynamic packing technology for injection molded part quality control and its production stability by using real-time PVT control method", Polymers, 2022; 14(2720): 16.

18 Chen, S. e al., "Prediction of part shrinkage for injection molded crystalline polymer via cavity pressure and mold temperature monitoring", Applied Sciences, 2023; 13(9884): 19.

19 Hassaan, G. A., "Thermoplastics injection molding machine control, Part III: Cavity gate pressure control using I-PD, PD-PI, 2DOF-2 controllers and I-P compensator compared with PID controller", International Journal of Research Publication and Reviews, 2024; 5(5): 4387-4398.

20 Mathworks, "Step response of dynamic system", https://www.mathworks.com/help/ident/ref/dynamicsystem.step.html, 2024.

21 Hassaan, G. A., "Tuning of an I-PD controller used with a highly oscillating second-order process", International Journal of Mechanical Engineering and Technology, 2014; 5(5): 115-121.

22 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, 2015; 1(3): 1-8.

23 Mohamed, M. R. and Hassaan, G. A., "Tuning of an I-PD controller for use with a third-order oscillating process", International Journal of Computer Techniques, 2020; 7(4): 1-6.

24 Hassaan, G. A., "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, 2024; 10(1): 13-24.

25 Hassaan, G. A., "Furnace control using I-PD, PD-PI and 2DOF controllers compared with fuzzy-neural controller. International Journal of Computer Techniques", 2024; 11(2): 1-10.

26 Messac, A., "Optimization in practice with MATLAB for engineering students and professionals", Cambridge University Press, 2015.

27 Martins, F. G., "Tuning PID controllers using the ITAE criterion", International Journal of Engineering Education, 2005; 21(5): 867-873.

28 Hassaan, G. A., "Control of a rocket pitch angle using PD-PI controller, feedback first-order compensator and I-PD compensator", International Journal of Computer techniques, 2024; 11(1): 1-8.

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

30 Hassaan, G. A. "Tuning of PD-PI controller used with first-order delayed process", International Journal of Engineering Research and Technology, 2014; 3(4): 51-55.

31 Hassaan, G. A. "Tuning of PD-PI controller used with a highly oscillating second-order process", International Journal of Science and Technology Research, 2014; 3(7): 145-147.

32 Hassaan, G. A., "Tuning of PD-PI controller used with an integrating plus time delay process", International Journal of Scientific & Technical Research, 2014; 3(9): 309-313.

33 Hassaan, G. A., "Controller tuning for disturbance rejection associated with delayed double integrator process, Part I: PD-PI controller", International Journal of Computer Techniques, 2015; 2(3): 110-115.

34 Hassaan, G. A., "Tuning of PD-PI controller used with a third-order process", International Journal of Application or Innovation in Engineering Management, 2020; 9(8): 6-12.

35 Hassaan, G. A., "Control of a boost-glide rocket engine using PD-PI, PI-PD and 2DOF controllers", International Journal of Research Publication and Reviews, 2023; 4(11): 913-923.

36 Hassaan, G. A., "Control of rocket pitch angle using PD-PI controller, feedback first-order compensator and I-PD compensator", International Journal of Computer Techniques, 2024; 11(1): 8.

37 Hassaan, G. A., "Liquefied natural gas tank pressure control using PID, PD-PI, PI-PD and 2DOF controllers", World Journal of Engineering Science and Technology, 2024; 10(2): 18-33.

38 Hassaan, G. A., "Control of boiler temperature using PID, PD-PI and 2DOF controllers", International Journal of Research Publication and Reviews, 2024; 5(1): 5054-5064.

39 Hassaan, G. A., "Control of Boiler-drum water level using PID, PD-PI, PI-PD and 2DOF controllers", International Journal of Engineering and Techniques, 2024; 10(1): 10.

40 Hassaan, G. A., "Tuning of PD-PI and PI-PD controllers to control the internal humidity of a greenhouse", International Journal of Engineering and Techniques, 2023; 9(4): 9.

41 Hassaan, G. A., "Tuning of controllers for reference input tracking of coupled-dual liquid tanks", World Journal of Engineering Science and Technology, 2022; 8(2): 86-101.
42 Hassaan, G. A., "Tuning of controllers for reference input tracking of a BLDC motor", International Journal of Progressive Research in Engineering, Management and Science, 2022; 2(4): 5-14.
43 Hassaan, G. A., "Furnace control using I-PD, PD-PI and 2DOF controllers compared with fuzzy-neural controller", International Journal of Computer Techniques, 2024; 11(2): 10.
44 Hassaan, G. A., "Control of an electro-hydraulic drive using PD-PI, PI-PD and 2DOF-2 controllers compared with a PID controller", International Journal of Engineering and Techniques, 2024; 10(2): 10.
45 Hassaan, G. A., "Strip thickness control using PD-PI, PI-PD and 2DOF-2 controllers compared with single model adaptive Smith predictor", International Journal of Computer Techniques, 2024; 11(2): 10.
46 Hassaan, G. A., "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, 2024; 10(3): 6-15.
47 Hassaan, G. A., "Tuning of a PI-PD controller used with a highly oscillating second-order process", International Journal of Research and Innovative Technology, 2014; 1(3): 42-45.
48 Singer, A., Hassaan, G. A. and Algamil, M, "Tuning of PI-PD controller used with a third-order process", World Journal of Engineering Research and Technology, 2020; 6(4): 367-375.
49 Hassaan, G. A., "Tuning of controllers for reference input tracking of a fourth-order blending process", World Journal of Engineering Research and Technology, 2022; 8(4): 177-199.
50 Hassaan, G. A., "Thermoplastics injection molding machine control, Part I: Mold temperature control using I-PD compensator, PD-PI and 2DOF-2 controllers compared with a PID controller", World Journal of Engineering Research and Technology, 2024; 10(5): 147-164.
51 Hassaan, G. A., "Tuning of a 2DOF controller for use with a highly oscillating second order process", International Journal of Modern Trends in Engineering and Research, 2015; 2(8): 292-298.

52. Nemati, H. and Bagheri, P. "A new approach to tune two-degree-of-freedom (2DOF)", IEEE International Symposium on Computer-aided Control System Design, Yokohama, Japan, 2010; 1819-1824.