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# Thermoplastics Injection Molding Machine (IMM) Control, Part VI: Full-Electric Control using PD-PI, PI-PD and 2DOF-4 Controllers Compared with a PI Controller

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**Abstract:**
This paper investigates the tuning of PD-PI, PI-PD and 2DOF-4 controllers from the second generation of PID controllers when used to control the injection velocity of a full-electric injection molding machine. 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. The disturbance rejection associated with the proposed controllers is improved through a special technique used by the author. The characteristics of the step time responses are compared with those of a PI conventional controller from the first generation of PID controllers. The best controller for both reference and disturbance inputs is assigned.
***Keywords*** — **Thermoplastics injection molding machine, all-electric IMM control, PD-PI controller, PI-PD controller, 2DOF-4 controller, PI controller, controller tuning.**

## I. INTRODUCTION

Full-electric injection molding machine are much cheaper than full-hydraulic machines and achieve great savings in energy consumption [1]. If this is true for energy consumption, what is is the situation for process control of a full-electric IMM (injection molding machine) ?. This research paper presents an answer for this this important industrial engineering question since control is the key approach for product high quality. Here are some of the research efforts regarding this subject:

Stack (2005) outlined that all-electric IMM's were developed to use electro-mechanical actuators instead of fluid power components (pumps, control valves, actuators). He investigated the potential of the all-electric technique including a case study comparing the performance of hydraulic and all-electric IMM producing similar parts. He calculated the specific energy consumption of each machine and found that the hydraulic machine required 0.278 kWh/lb of processed plastic compared to 0.073 kWh/lb for the all-electric machine [1]. Yan and Su (2011) studied a full-motor IMM velocity tracking control system based on model predictive control. They claimed that their control system had strong robustness and anti-interference ability and could improve the control performance [2]. Iwazaki, Ohishi and Urushihara (2014) proposed a friction-free observer for the robust sensorless pressure control of an IMM. They experimentally confirmed the estimation performance of the proposed friction-free observer using different driving points [3].

Chen, Dinh and Nguyen (2017) studied two research aspects: double servomotors synchronization control for an IMM and filling to packing switchover methods. They performed modeling, control, simulation and experimental implementation [4]. Veligorskyi, Chakirov and Vagapov (2019) proposed an artificial neural network-based position controller for a full-electric IMM. They used experimental data and MATLAB identification toolbox to identify the transfer functions of the motors. They estimated the efficiency of the proposed ANN-based controller and verified using Simulink. They used a 2/3 order transfer function for the motor and linear actuator of the IMM [5]. Vukovic et al. (2022) proposed an adaptive cross-phase cavity pressure control based on only one nonlinear time-variant model for the entire IMM process. They adapted the controller model to the time varying process dynamics using a Kalman filter. They provided guidelines for the model tuning parameters and validated the controller concept on two different IMM for two different moulded parts showing good reference tracking capabilities [6].

Kariminejad, Tormey and McAfee (2024) mathematically modeled the injection and packing phases and outlined the design of a proposed model-based controller for the injection and cavity pressures. They explored the ability of the designed controller to follow a set pressure profile. They used a second-order model with time delay for a servo-electric drive between an input voltage and drive velocity [7].

## II. THE CONTROLLED PROCESS

The controlled process is a full-electric injection molding machine replacing the full-hydraulic driving system. The line-diagram construction of a full-electric IMM is shown in Fig.1 [2] where one motor is responsible for the injection speed of the IMM and another motor is responsible for the rotational speed of its screw to feed the plastic towards the mold while milting it.

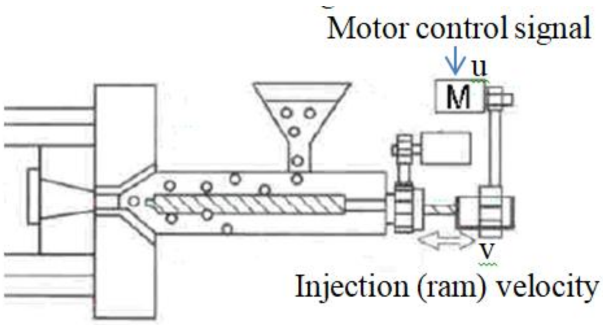



Fig.1 Full-electric IMM construction [2].

The open-loop transfer function of the motor-screw dynamic system between the control signal U(s) and the injection speed (ram velocity) V(s), $G_p(s)$ is given by [7]:

$$G_p(s) = V(s)/U(s) = K\,\omega_o^2 \exp(-T_d s) / (s^2 + 2\zeta\omega_o s + \omega_o^2) \quad (1)$$

Where: $\omega_o$ = natural frequency of the dynamic system = 133 rad/s

$\zeta$ = damping ration of the dynamic system = 0.79

K = gain of the dynamic system = 23.4 (mm/s)/V

$T_d$ =delay time of the dynamic system (not assigned in reference [7]).

To simplify the dynamic analysis of the control system with exponential term in the process transfer function, a second-order Pade approximation is used replace the exponential term with a rational approximation terms [8] as follows:

$$\exp(-T_d s) \approx (T_d^2 s^2 - 6T_d s + 12) / (T_d^2 s^2 + 6T_d s + 12) \quad (2)$$

Eqs.1 and 2 are used to assign the process transfer function in terms of the time delay and plot the unit-step time response of the injection speed of the IMM using the MATLAB command '*step*' [9] which is shown in Fig.2 for three levels of the motor-screw time delay.

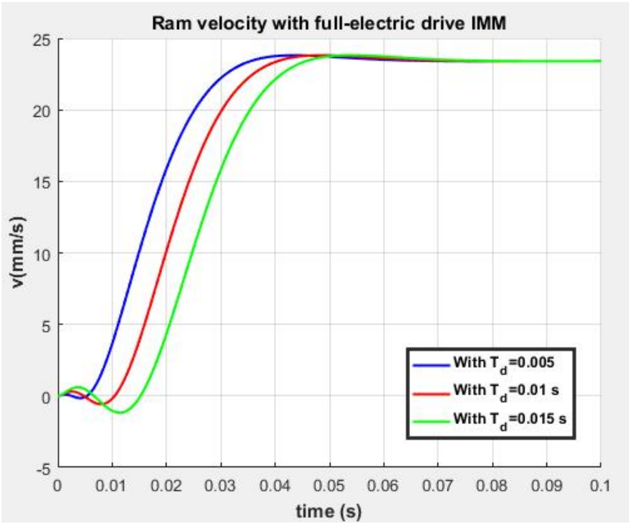



Fig.2 Step time response of the full-electric IMM.

Fig.2 reveals the following dynamic characteristics of the full-electric IMM under study:

- For $T_d$ = 0.005 s:
  - Maximum overshoot: 1.752 %
  - Maximum undershoot: -0.154 mm/s
  - Settling time: 0.0326 s
  - Steady-state error: --22.4 mm/s
- For $T_d$ = 0.010 s:
  - Maximum overshoot: 1.765 %
  - Maximum undershoot: -0.577 mm/s
  - Settling time: 0.0376 s
  - Steady-state error: --22.4 mm/s
- For $T_d$ = 0.015 s:
  - Maximum overshoot: 1.794 %
  - Maximum undershoot: -1.174 mm/s
  - Settling time: 0.0430 s
  - Steady-state error: --22.4 mm/s

This is another example of bad processes that has to be controlled to overcome its bad dynamics of very large steady-state error and increasing maximum undershoot as the time delay increases. 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. FULL-ELECTRIC IMM 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 [10], integrating plus time delay process [11], delayed double integrating process [12], overdamped second-order processes [13], fourth-order blending process [14], coupled dual tanks [15], internal humidity of a greenhouse [16], rocket pitch angle [17], liquefied natural gas tank pressure [18], liquefied natural gas tank level [19], boiler temperature [20], boiler drum water level [21], furnace temperature [22], electro-hydraulic drive [23], rolling strip thickness [24], injection molding mold temperature [25], IMM barrel temperature [26], IMM cavity gate pressure [27], IMM mold packing pressure [28] and IMM ram velocity [29].
- 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 [16]:

$$G_{PDPI}(s)=[K_dK_{pc2}s^2+(K_{pc1}K_{pc2}+K_dK_i)s+K_{pc1}K_i]/s \quad (3)$$

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 transfer function of the full-electric IMM motor-screw system for a 0.01 s time delay is used in the tuning operation of all the proposed controllers. It is given using Eqs.1 and 2 by:

$$G_p(s) = (41.39s^2-24840s+4.967x10^6) / (0.0001s^4+0.08101s^3+26.38s^2+3583s+212268) \quad (4)$$

- 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, controller transfer function in Eq.3, process transfer function in Eq.4 and the '*step*' command of MATLAB [9].
- 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 [30] is minimised using the MATLAB optimization toolbox [31].
- 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:

$$K_{pc1} = 1.963180 \quad ; \quad K_d = 0.001652$$
$$K_{pc2} = 0.001515 \quad ; \quad K_i = 0.437625 \quad (5)$$

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [9] using the PD-PI controller tuned gain parameters in Eq.5 and its transfer functions is shown in Fig.3.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: zero
  - Maximum undershoot: -0.00232 mm/s
  - Settling time: 0.123 s
- For disturbance rejection using the tuned PD-PI controller (without filter receiving the disturbance input):
  - Maximum step time response: 0.0044 mm/s

- Minimum step time response: -0.0025 mm/s
- Settling time (with filter) to zero: 0.1 s

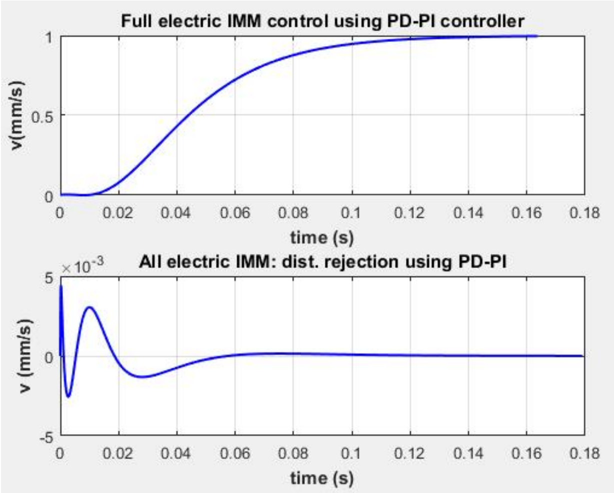



Fig.3 Step time response of the PD-PI controlled full-electric IMM.

## IV. FULL-ELECTRIC IMM 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 [32], third-order process [33], greenhouse humidity [16], fourth-order blending process [14], boost-glide rocket engine [34], BLDC motor [35], boiler drum water level [21], electro-hydraulic drive [23], rolling strip thickness [24], IMM barrel temperature [26], IMM cavity gate pressure [27], IMM packing pressure [28] and IMM ram velocity [29].
- The block diagram of a control system incorporating a PI-PD controller controlling the full-electric IMM is shown in Fig.4 [23].
- 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.

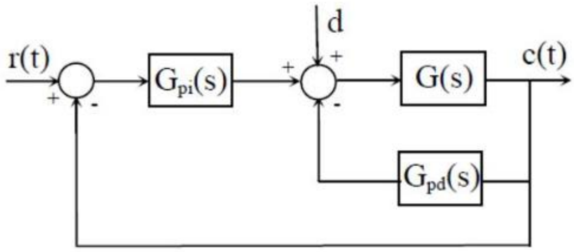



Fig.4 Block diagram of a PI-PD controlled process [23].

- The PI-PD controller elements have the transfer functions:

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

And $G_{PD}(s) = K_{pc2} + K_d s$ (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.4 are derived from the block diagram using Eqs.4 for the process and 6 for the PI-PD controller for both inputs R(s) and D(s).
- The unit step time response of the control system, v(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 [9].
- 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 [30] is minimised using the MATLAB optimization toolbox [31].
- Minimizing the error function ITAE reveals the following optimal gain parameters of the PI-PD controller:

$K_{pc1} = 0.018693$ ; $K_i = 0.7610157$

$K_{pc2} = -0.019989$ ; $K_d = -0.000084$ (7)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' [9] using the PI-PD controller tuned gain parameters in Eq.7 and shown in Fig.5.

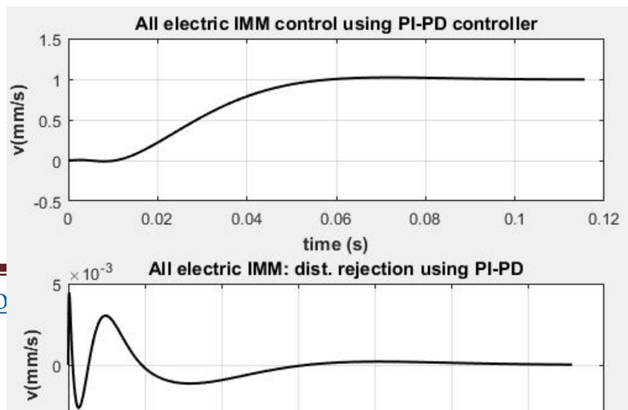


Fig.5 Step time response of the PI-PD controlled full-electric IMM.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 2.034 %
  - Maximum undershoot: -0.0107 mm/s
  - Settling time: 0.074 s
- For disturbance rejection using the tuned PI-PD controller:
  - Maximum step time response: 0.00442 mm/s
  - Minimum step time response: -0.00269
  - Settling time (without using filter): 0.12 s

## V. FULL-ELECTRIC IMM CONTROL USING A 2DOF-4 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 [18], liquefied natural gas level control [19], boost-glide rocket engine [35], BLDC motor control [35], highly oscillating second-order process [36], delayed double integrating processes [37], second-order-like processes [38], furnace temperature [22], gas turbine speed [39], greenhouse temperature control [40], LNG tank pressure [18], LNG tank level [19], boiler temperature [20], boiler drum water level [21], electro-hydraulic drive [23], rolling strip thickness [24], IMM mold temperature [25], IMM cavity gate pressure [27], IMM packing pressure [28] and IMM ram velocity [29].
- 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.6 [29].

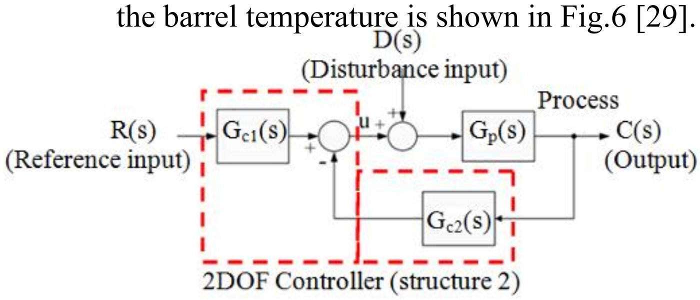



Fig.6 Block diagram of 2DOF-4 controlled process [29].

- The 2DOF-4 controller is a new version of the 2DOF controller structure aiming at simplifying the structure of the controller for its electronic structure and hence its cost. It is composed of two elements: PD-control-mode of $G_{c1}(s)$ transfer function in a forward path receiving the reference input and a P-control mode of $G_{c2}(s)$ transfer function in the feedback path of the control system loop.
- The 2DOF-4 controller elements have the transfer functions:

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

And $G_{c2}(s) = K_{pc2}$ (8)

- The 2DOF-4 controller has three gain parameters $K_{pc1}$, $K_d$ and $K_{pc2}$ to be tuned to adjust the performance of the closed-loop control system.
- The transfer functions of the closed-loop control system in Fig.6 are derived from the block diagram using Eqs.4 for the process and 8 for the 2DOF-4 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 [9].

- Investigating the closed loop transfer function of the control system with reference input tracking reveals a condition relating some of the 2DOF-4 controller to each other for a zero steady state error.
- In such a case, 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 [30].
- Minimizing the error function ITAE reveals the following optimal gain parameters of the 2DOF-2 controller:

$K_{pc1} = 0.0066254$ ; $K_d = 0.0006436$

$K_{pc2} = 0.00062013$ (9)

- The unit step time response of the control system for reference and disturbance inputs as generated by the MATLAB command '*plot*' using the 2DOF-4 controller tuned gain parameters in Eq.9 and shown in Fig.7.

COMMENTS:

- For the reference input tracking step time response:
  - Maximum percentage overshoot: 1.416 %
  - Maximum undershoot: -0.163 mm/s
  - Settling time: 0.0204 s
- For disturbance rejection using the tuned 2DOF-4 controller:
  - Maximum step time response: 0.0044 mm/s
  - Minimum step time response: -0.0025 mm/s
  - Settling time (without using filter): 0.07 s

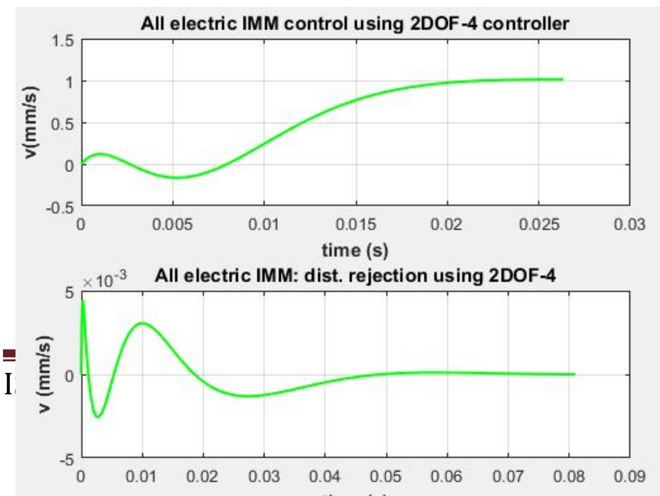



Fig.7 Step time response of the 2DOF-4 controlled full-electric IMM .

## VI. COMPARISON OF TIME BASED CHARACTERISTICS

- Graphical comparison for both reference and disturbance inputs: Presented in Figs.8 and 9.
- 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 proposed controllers is presented in Tables 1 and 2 with comparison with the application of a conventional PI controller used to control the same process.

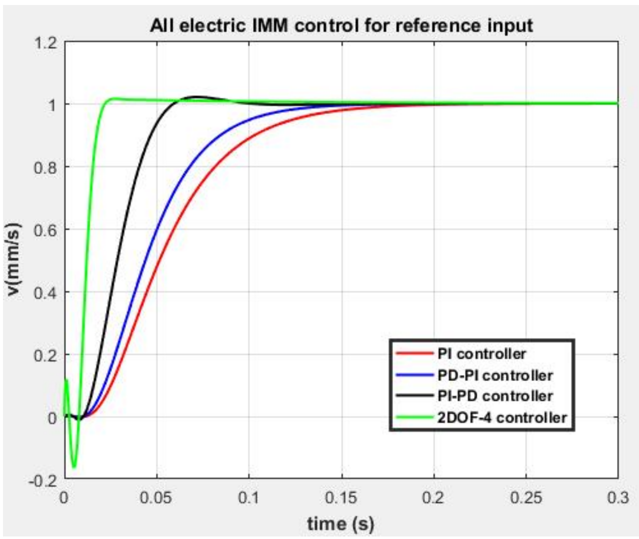



Fig.8 Comparison of the step reference input time response for a full-electric IMM.

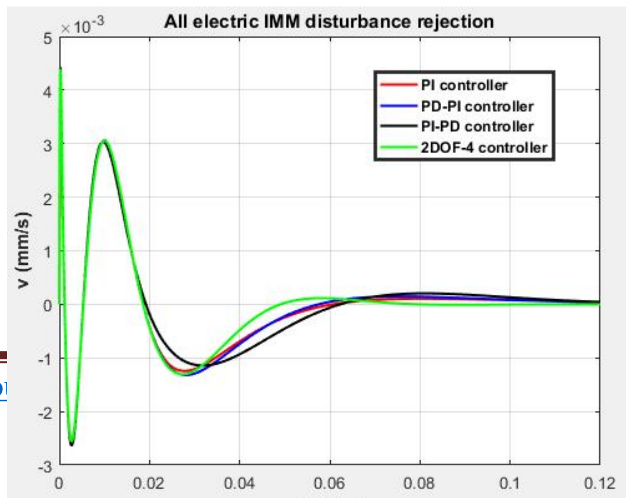


Fig.9 Step disturbance input time response comparison for full-electric IMM.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF THE FULL-ELECTRIC IMM

| Controller | PD-PI | PI-PD | 2DOF-4 | PI |
|---|---|---|---|---|
| $OS_{max}$ (%) | 0 | 2.034 | 1.416 | 0 |
| $US_{max}$ (mm/s) | -0.0023 | -0.0107 | -0.163 | -0.0012 |
| $T_s$ (s) | 0.123 | 0.074 | 0.0204 | 0.153 |

TABLE 2
TIME-BASED CHARACTERISTICS FOR DISTURBANCE INPUT REJECTION

| Controller | PD-PI | PI-PD | 2DOF-4 | PI |
|---|---|---|---|---|
| $v_{Dmax}$ (mm/s) | 0.0044 | 0.0044 | 0.0044 | 0.00428 |
| $v_{Dmin}$ (mm/s) | -0.0025 | -0.0027 | -0.0025 | -0.00255 |
| $T_{s0}$ (s) | 0.10 | 0.12 | 0.07 | 0.10 |

## VII. CONCLUSIONS

- The research work presented in this research paper handled the tuning of PD-PI, PI-PD and 2DOF-4 controllers used to control a full-electric IMM.
- The paper presented a novel version of the 2DOF controller that could suppress the disturbance effect in only 70 ms and generate reference input tracking with only 20 ms settling time.
- The controlled process was a stable one with bad dynamics of very large steady-state error of -22.4 mm/s to its unit reference input putting a real challenge for any proposed controller.
- The full-electric IMM controlled process had a delayed second order transfer function.
- The delayed term was replaced by a second-order Pade approximation producing a 2/3 transfer function without time delay.
- To control the full-electric IMM one controller from the first PID generation (PI controller) and three controllers from the second generation (PD-PI, PI-PD and 2DOF-4 controllers) were proposed.
- The four 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.
- Because of the high efficiency of the used tuning procedure, the conventional PI controller could produce a step time response without any overshoot, with a settling time of only 15.3 ms and disturbance rejection characteristics comparable with the other second-generation controllers.
- The PD-PI controller could generate a step time response without any overshoot and with a settling time of 12.3 ms.
- The PI-PD controller succeeded to produce a step time response with maximum percentage overshoot to 2.034 % with 74 ms settling time.
- The novel 2DOF-4 controller succeeded to produce a step time response with 1.416 % maximum percentage overshoot and 20.4 ms settling time and the best characteristics for the disturbance rejection associated with the process disturbance input.
- The PD-PI controller was selected as the best controller regarding reference input tracking if the selection criterion is the maximum overshoot. If the selection criterion is the settling time, then the 2DOF-4 controller is the best.
- Regarding disturbance rejection associated with the full-electric IMM process, the 2DOF-4 is the best selection.

## REFERENCES

1. *M. Socks, "The promise of all-electric injection molding machines: A promise kept?", ACEEE*

Summer Study on Energy Efficiency in Industry, Paper 1, pp.155-166, 2005.

2. X. Yan and S. Su, "Model predictive control for velocity tracking in full-motor injection molding", Advanced Materials Research, vol.271-273, pp.541-545, 2011.
3. K. Iwazaki, K. Ohishi and S. Urushihara, "Robust sensorless pressure control of electric injection molding machine using friction-free force observer", IEEE 13th International Workshop on Advanced Motion Control, pp.43-48, 2014.
4. S. Chen, H. Dinh and V. Nguyen, "Synchronized injection molding machine with servomotors", Advances in Technology Innovation, vol.2, issue 2, pp.34-39, 2017.
5. O. Veligorskyi, R. Chakirov, M. Khomenko and Y. Vagapov , "Artificial neural network motor control for full-electric injection molding machine", IEEE International Conference on Industrial Technology, Melbourne, Australia, 13-15 February,6 pages , 2019.
6. M. Vukovic, S. Stemmler, K. Hornberg, D. Abel and C. Hopmann, "Adaptive model based predictive control for cross-phase cavity pressure control in injection molding", Journal of Manufacturing Processes, vol.77, pp.730-742, 2022.
7. M.Kariminejad, D. Tormey and M. McAfee, " Model-based pressure tracking using a feedback linearization technique in thermoplastic injection molding", ArXiv: 2403.04388, Systems and Control, 17 pages, 2024.
8. V. Hanta and A. Prochazka, "Rational approximation of time delay", Institution of Chemical Technology, Prague, Department of Computing and Control Engineering, vol.5, issue 22, 7 pages, 2009.
9. Mathworks, "Step response of dynamic system", https://www.mathworks.com/help/ident/ref/dynamicsystem.step.html, 2023.
10. G. A. Hassaan, "Tuning of a PD-PI controller used with a highly oscillating second-order process", International Journal of Scientific and Technology Research, vol.3, issue 7, pp.145-147, 2014.
11. G. A. Hassaan, "Tuning of a PD-PI controller used with an integrating plus time delay process", International Journal of Scientific and Technology Research, vol.3, issue 9, pp.309-313, 2014.
12. G. A. Hassaan, "Controller tuning for disturbance rejection associated with a delayed double integrating process", International Journal of Computer Techniques, vol.2, issue 3, pp.110-115, 2015.
13. G. A. Hassaan, "Tuning of a PD-PI controller to control overdamped second-order processes", International Journal of Engineering and Research Publication and Reviews, vol.2, issue 12, pp.1042-1047, 2021.
14. G. A. Hassaan, "Tuning of controllers for reference input tracking of a fourth-order blending process", World Journal of Engineering Research and Technology, vol.8, issue 4, pp.177-199, 2022.
15. G. A. Hassaan, "Tuning of controllers for reference input tracking of coupled-dual liquid tanks", World Journal of Engineering Research and Technology, vol.8, issue 2, pp.86-101, 2022.
16. G. A. Hassaan, "Tuning of PD-PI and PI-PD controllers to control the internal humidity of a greenhouse", International Journal of Engineering Techniques, vol.9, issue 4, 9 pages, 2023.
17. G. A. Hassaan, "Control of a rocket pitch angle using PD-PI controller, feedback first-order compensator and I-PD compensator", International Journal of Computer Techniques, vol.11, issue 1, 8 pages, 2024.
18. G. A. Hassaan, "Liquefied natural gas tank pressure control using PID, PD-PI and 2DOF controllers", World Journal of Engineering Research and Technology, vol.10, issue 2, pp.18-33, 2024.
19. G. A. Hassaan, "Liquefied natural gas tank level control using PD-PI, I-PD and 2DOF controllers", World Journal of Engineering Research and Technology, vol.10, issue 1, pp.13-26, 2024
20. G. A. Hassaan, "Control of boiler temperature using PID, PD-PI and 2DOF controllers", International Journal of Research Publication and Reviews, vol.5, issue 1, pp.5054-5064, 2024.
21. G. A. Hassaan, "Control of boiler drum water level using PID, PD-PI PI-PD and 2DOF

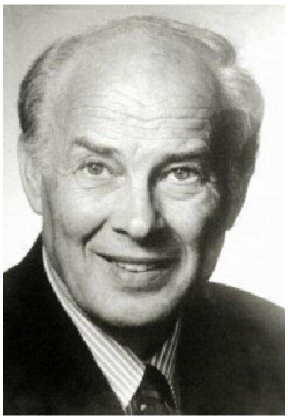
*controllers", International Journal of Engineering and Techniques, vol.10, issue 1, 10 pages, 2024.*

22. *G. A. Hassaan, "Furnace control using I-PD, PD-PI and 2DOF controllers compared with fuzzy-neural controller", International Journal of Computer Techniques, vol.11, issue 2, 10 pages, 2024.*
23. *G. A. Hassaan, "Control of an electro-hydraulic drive using PD-PI PI-PD and 2DOF controllers compared with PID controller", International Journal of Engineering and Techniques, vol.10, issue 2, 10 pages, 2024.*
24. *G. A. Hassaan, "Rolling strip thickness control using PD-PI, Pi-PD and 2DOF controllers compared with single model adaptive Smith predictor", International Journal of Computer Techniques, vol.11, issue 2, 10 pages, 2024.*
25. *G. A. Hassaan, "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, vol.10, issue 5, pp.147-164, 2024.*
26. *G. A. Hassaan, "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, vol.10, issue 3, pp.6-15, 2024.*
27. *G. A. Hassaan, "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 a PID controller", International Journal of Research Publication and Reviews, vol.5, issue 5, pp.4387-4398, 2024.*
28. *G. A. Hassaan, "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", World Journal of Engineering Research and Technology, vol.10, issue 6, pp.94-114, 2024.*
29. *G. A. Hassaan, "Thermoplastics injection molding machine control, part V:Ram velocity control using I-PD, PD-PI, PI-PD and 2DOF-3 controllers compared with improved PID controller", International Journal of Computer Techniques, vol.11, issue 3, pp.42-52, 2024.*
30. *F. G. Martins, "Tuning PID controllers using the ITAE criterion", International Journal of Engineering Education, vol.21, issue 5, pp.867-873, 2005.*
31. *C. P. Lopez, "MATLAB optimization techniques", Apress, 2014.*
32. *G. A. Hassaan, "Tuning of a PI-PD controller used with a highly oscillating second-order process", International Journal of Research and Innovative Technology, vol.1, issue 3, pp.42-45, 2014.*
33. *A. Singer, G. A. Hassaan and M. Elgamil, "Tuning of a PI-PD controller used with a third-order process", World Journal of Engineering Research and Technology, vol.8, issue 4, pp.367-375, 2020.*
34. *G. A. Hassaan, "Control of a boost-glide rocket engine using PD-PI, PI-PD and 2DOF controllers", International Journal of Research Publication and Reviews, vol.4, issue 11, pp.913-923, 2023.*
35. *G. A. Hassaan, "Tuning of controllers for reference input tracking of a BLDC motor", International Journal of Progressive Research in Engineering, Management and Science, vol.2, issue 4, pp.5-14, 2022.*
36. *G. A. Hassaan, "Tuning of a 2DOF controller for use with a highly oscillating second-order-like process", International Journal of Modern Trends in Engineering and Research, vol.2, issue 8, pp.292-298, 2015.*
37. *G. A. Hassaan, "Controller tuning for disturbance rejection associated with delayed double integrating process, Part V: 2DOF controller", International Journal of Engineering and Techniques, vol.1, issue 4, pp.26-31, 2015.*
38. *G. A. Hassaan, "Tuning of a feedforward 2DOF PID controller to control second-order-like processes", International Journal of Engineering and Techniques, vol.4, issue 4, pp.135-142, 2018.*
39. *G. A. Hassaan, "Tuning of 2DOF controllers for the speed control of a gas turbine",*

*International Journal of Engineering and Techniques, vol.8, issue 2, pp.35-44, 2022.*

**40.** *G. A. Hassaan, "Temperature control of a greenhouse using PD-PI, PI-PD and 2DOF controllers", International Journal of Engineering Inventions, vol.12, issue 9, pp.156-162, 2023.*

**DEDICATION**



**Late Prof. John Parnaby**

- Father of '*industrial engineering*' in 1970's.
- Worked in Solway Chemical Company in 1966 as a 'Works Director'.
- His Ph. D. was about the 'design of electrohydraulic control systems'.
- He was interested in 'computer modeling and control'.
- He joined Bradford University (UK) in 1970.
- He was appointed as the 'first professor of manufacturing systems engineering' in Britain.
- He was the chairman of the Industrial Engineering Department of the Bradford University.
- In 1983, he joined Lucas Industries as a 'Group Director of Technology'.
- He became 'Group Director' in the merged Lucas Varity serving until reaching retirement in 1997.
- He was elected as 'President of the Institute of Production Engineering'.
- After retirement he served as Royal Academy of Engineering visiting professor at Cambridge.
- He acted as a Treasurer' for Aston University for 6 years.
- He died on 5th January 2011.
- I was his Ph. D. student from 1975-1979 working in 'computer control of plastics extruder'.
- How great you were. I learned automatic control from you. Thanks dear professor.

**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.
- 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.
- Chief Justice of the International Journal of Computer Techniques.
- Member of the Editorial Board of IJET.
- Reviewer in some international journals.
- Scholars interested in the authors publications can visit:

**http://scholar.cu.edu.eg/galal**