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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

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Abstract:

The paper is the fifth in a series of research papers dealing with the control of thermoplastics injection molding machines. It proposes four controllers: I-PD, PD-PI, PI-PD and 2DOF-3 controllers from the second generation of PID controllers to control ram velocity of the injection molding machine. The gain parameters of the four controllers are tuned to provide optimal performance for the control system providing better characteristics in terms of maximum percentage overshoot, settling time and steady-state accuracy (minimum error). The ITAE performance index is selected for the four proposed controllers and their step time response for reference input tacking is compared with an improved PID controller used to control the same process in a previous research work. The best controller is assigned for both reference input tracking and disturbance rejection based on the best performance provided.

Keywords — Ram v**elocity control, I-PD controller, PD-PI controller, PI-PD controller, 2DOF-3, controller tuning.**

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I. INTRODUCTION

Plastics production using injection molding machines is one of the key industries in all over the world. However, because plastics are sensitive to the variation in its operating variables, process control is vital in having high quality products. Control engineers are trying to introduce new controllers every day because of those circumferences. As a research engineer I try to help machine designers and control engineers to select and design simple controllers but very efficient in producing control systems with high performance compared with other control techniques. In the fifth paper of a series aiming at controlling the injection molding machine, ram velocity (or injection rate) is considered and four controllers are proposed. We start by having an overview of some of the research efforts aiming at controlling the ram velocity of the injection molding machine.

Tian and Gao (1999) analyzed the injection velocity dynamics and introduced a double controller scheme for the injection velocity control. Special techniques of profile transformation and shifting were introduced to improve the velocity response. They claimed that their control technique was effective for a wide range of processing conditions [1]. Tan, Huang and Jiang (2001) presented a design for an adaptive controller for the control of the ram velocity f an injection molding machine based on a nonlinear model describing the filling process. They defined a sliding surface and proposed a self-tuning robust controller where the controller gains were tuned by an adaptive algorithm. They provided simulation to evaluate the performance of the proposed control system [2]. Huang, Tan and Lee (2004) developed a predictive learning controller for ram velocity control based on neural network. They introduced a model for the injection molding process including the time horizon and the batch index. The weights of the radial basis function were determined by the predictive control scheme based on the batch index. They claimed that their proposed control scheme was robust against system uncertainties and could reject repeated disturbances [3].

Wang, Ying, Zhou and Ke (2009) presented an energy-saving servo injection control system using fuzzy control theory based on a mathematical model of a servo-motor driving a fixed pump. They claimed that simulation showed that the fuzzy controller could effectively reduce the injection velocity tracking error and the proposed control system was a good-robust compared with conventional PID controller [4]. Feriyonika and Dewantoro (2013) analyzed the injection velocity of an injection molding process. They outlined that the injection velocity in injection molding machines is difficult to control by some classical control methods. They proposed robust and adaptive control using fuzzy-sliding mode control to control the injection velocity in a finite time. Simulation results showed that their proposed control could decrease the chattering phenomenon and followed the velocity set point with small error [5]. Frohlich, Kemmetmuller and Kugi (2018) presented a computationally efficient and scalable mathematical model for the injection molding process in servovalve driven injection molding machines. They claimed that their model confirmed high accuracy over the whole operating range for different mold geometries. They outlined that their model was an ideal basis for the design of model-based control strategies [6].

Veligorskyi and Chakirov (2019) proposed an artificial neural network-based position controller for a full-electric injection molding machine. They used experimental data and MATLAB identification toolbox to identify the motor transfer functions. They trained the ANN to control the identified motor current for the required position and velocity [7]. Tang et al. (2021) used a PID controller with integral and derivative terms improved using an unsaturated integral and derivative terms to achieve good control effect. They constructed the transfer function of the injection system and used it with the improved PID controller. Simulation and experimentation were used to verify the use of the improved PID controller showing no overshoot, rapid step time response and high precision [8].

Ren, Wu and Xie (2022) studied the optimal tracking injection velocity control problem using a typical injection molding machine. They developed a hybrid intelligent control based on deep learning to mimic the classical model predictive control rule to deal with the tracking control of the injection speed. They outlined that their approach had benefits over the conventional optimization method illustrated through simulation results showing more robustness and resistance to environmental uncertainties [9]. Wu, Ren, Li and Wu (2023) focused on solving an optimal tracking control problem of the injection velocity arising in a typical nonlinear injection molding machine. They proposed and designed an efficient optimal robust controller. Their proposed controller was based on Ricatti equation used to construct an optimal robust feedback controller and Lyapunov theorem analysis was implemented to assign the global stability and the proposed feedback controller. They showed through simulation the best tracking of the intended injection velocity trajectory within a given time [10].

II. THE CONTROLLED RAM VELOCITY AS A PROCESS

Yang et al. used an improved PID controller to control the injection rate (ram velocity) of an injection molding machine. They used a fourth-order transfer function model for the ram velocity, $G_p(s)$ given by [8]:

$$G_p(s) = \frac{2.167\text{x}10^{11}}{(s+130)(s+1140)[(s+390)^2+(1138)^2]} \qquad (1)$$

Writing Eq.1 in a standard form gives the ram speed transfer function as:

$$G_p(s) = \frac{2.167\text{x}10^{11}}{S^4+2050s^3+2.586\text{x}10^6 s^2+1.953\text{x}10^9 s+ 2.145\text{x}10^{11}} \qquad (2)$$

. The fourth-order process of the ram velocity has unit step time response shown in Fig.1 as generated by the step command of MATLAB [11].

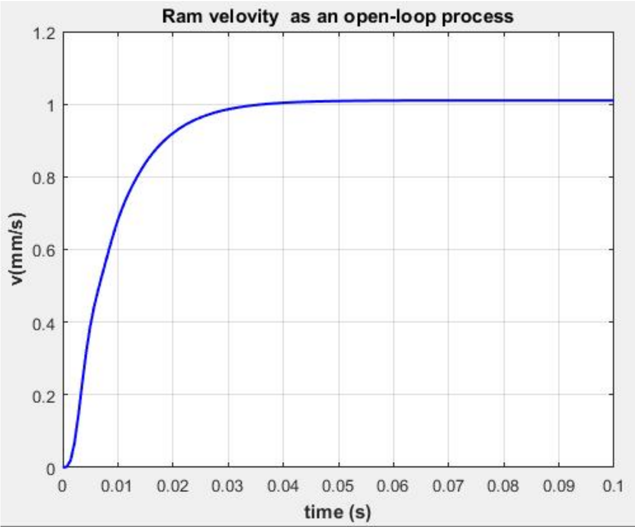

Fig.1 Open-loop step time response of the ram velocity.

- The ram velocity as an open-loop dynamic system has the dynamic characteristics:
  - Maximum overshoot: zero
  - Settling time: 0.0315 s
  - Steady-state error: -0.0104 mm/s
- This process dynamically has good dynamics because of its zero overshoot, small settling time and good steady-state characteristics.

III. CONTROLLING THE RAM VELOCITY 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 [12], delayed double integrating process [13], third-order process [14], liquefied natural gas tank level [15], furnace temperature control [16] and cavity gate pressure of an injection molding machine [17].

The block diagram of a control system incorporating an I-PD controller and the ram velocity process is shown in Fig.2 [17].

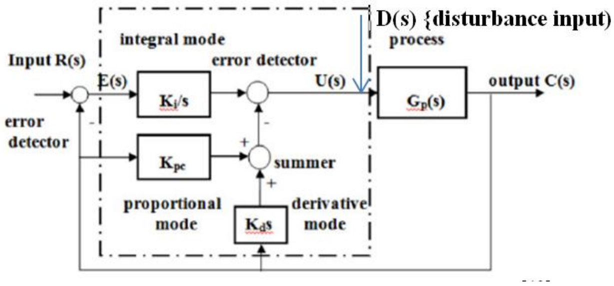

Fig.2 Structure of the I-PD controller [17].

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

$$G_I(s) = K_i/s$$
$$G_P(s) = K_{pc} \quad (3)$$
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 [18] and an ITAE performance index [19]. The tuned gain parameters of the I-PD controller are:

$$K_i = 23084.953 \quad , \quad K_{pc} = 0.0002145$$
$$K_d = 16.89640 \quad (4)$$

- The unit step time response of the control system for the cavity packing pressure with reference and disturbance inputs using Eqs.2, 3 and 4 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: 0.743 s

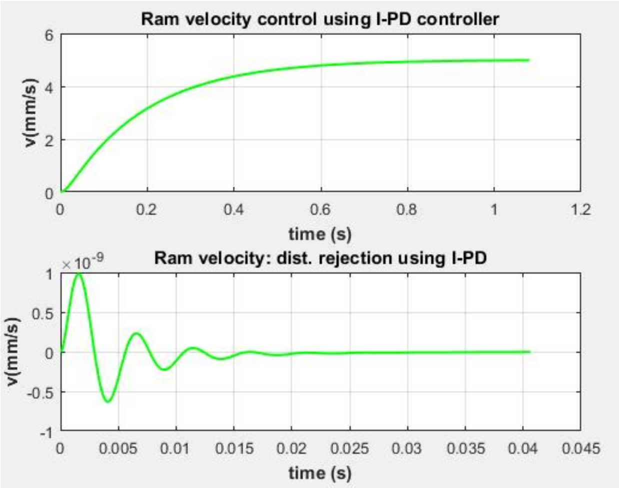

Fig.3 Ram velocity control using an I-PD controller.

- 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 ram velocity step time response: 0.980×10^{-9} mm/s
  - Minimum ram velocity step time response: -0.630×10^{-9} mm/s
  - Settling time to zero (approximate): 0.03 s

IV. CONTROLLING THE RAM VELOCITY USING A PD-PI CONTROLLER

The PD-PI controller was introduced by the author in 2014 as one of the good controllers of the second generation of the PID controllers. The author tested the performance of the PD-PI controller through its use in controlling first-order delayed processes [20], highly oscillating second-order process [21], integrating plus time-delay process [22], delayed double integrating process [23], third-order process [24], boost-glide rocket engine [25], rocket pitch angle [26], LNG tank pressure [27], boiler temperature [28] boiler-drum water level [29], greenhouse internal humidity [30], coupled dual liquid tanks [31], BLDC motor [32], furnace temperature [33], electro-hydraulic drive [34], barrel temperature [35] and mold packing pressure [36].

The block diagram of the control system incorporating a PD-PI controller comprises a PD-control and PI-control modes in series after the error detector feeding its output directly to the controlled process.

The PD-PI controller has a transfer function, $G_{PDPI}(s)$ given by [30]:

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

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 = derivative gain of the PI-control mode

The PD-PI controller has four gain parameters to be tuned to optimal performance for the control system.

- The transfer function of the control system comprising the PD-PI controller and the controlled process is derived using the block diagram of the control system and Eqs.2 and 5.
- The performance index to me minimized by the optimization technique was selected as the ITAE [19].
- The MATLAB optimization toolbox [18] is selected to perform the minimization of the ITAE and provide the optimal gain parameters of the PD-PI controller.
- The tuned parameters of the PD-PI controller are as follows:

$K_{pc1} = 16.994240$, $K_d = 0.435416$

$K_{pc2} = 0.003200$, $K_i = 2.698448$ (6)

- Using the closed-loop transfer function of the closed-loop control system and the PD-PI controller gains in Eq.6 with reference input and zero disturbance input and the transfer function of the closed-loop control system with disturbance input and zero reference input, the unit step response is shown in Fig.4.

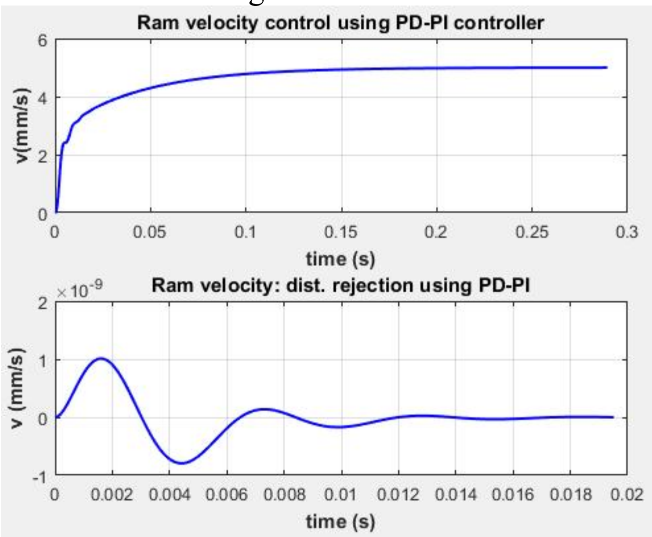

Fig.4 Ram velocity control using a PD-PI controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - ➢ Maximum percentage overshoot: zero
  - ➢ Settling time: 0.135 s
- Control system characteristics for disturbance rejection:
  - ➢ Maximum time response: 1.01×10^{-9} mm/s
  - ➢ Minimum time response: -0.79×10^{-9} mm/s
  - ➢ Settling time to zero: 0.018 s

V. CONTROLLING THE RAM VELOCITY USING A PI-PD CONTROLLER

The PI-PD controller was introduced by the author in 2014 as one of the good controllers of the second generation of the PID controllers. The author tested the performance of the PI-PD controller through its use in controlling a highly oscillating second-order process [38], second-order processes [39], delayed double integrating process [40], third-order process [37], boost-glide rocket engine [25], LNG tank pressure [27], boiler-drum water level [29], greenhouse internal humidity [30], coupled dual liquid tanks [31], BLDC motor [32], electro-hydraulic drive [34], barrel temperature [35] and mold packing pressure [36].

The block diagram of the control system incorporated the PI-PD controller is shown in Fig.5 [41]. It is composed of a forward element which is a PI control mode and a feedback element in an internal loop about the process which is a PD control mode.

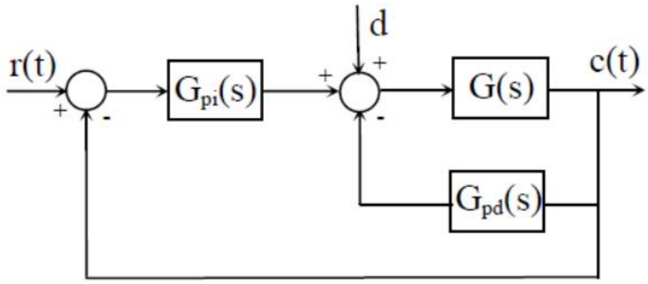

Fig.5 Structure of the PI-PD controller [41].

The PI-PD controller elements have the transfer functions:

$$G_{PI}(s) = K_{pc1} + (K_i/s)$$
$$G_{PD}(s) = K_{pc2} + K_d s \qquad (7)$$

Where:

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

K_i = integral gain of the PI-control mode

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

K_d = derivative gain of the PD-control mode

The PI-PD controller has four gain parameters to be tuned to provide the optimal performance of the control system. The tuning technique is the same as that used in the PD-PI controller in the previous section.

- The tuned parameters of the PI-PD controller are as follows:

$K_{pc1} = 0.674691$, $K_i = 105.010825$
$K_{pc2} = 0.698164$, $K_d = 0.002763$ (8)

- Using the closed-loop transfer function of the closed-loop control system and the PI-PD controller (using the block diagram in Fig.5 with zero disturbance signal) and the controller gains in Eq.7 with reference input and the transfer function of the closed-loop control system with disturbance input and zero reference input, the unit step response of the control system incorporating the PI-PD controller is shown in Fig.6.

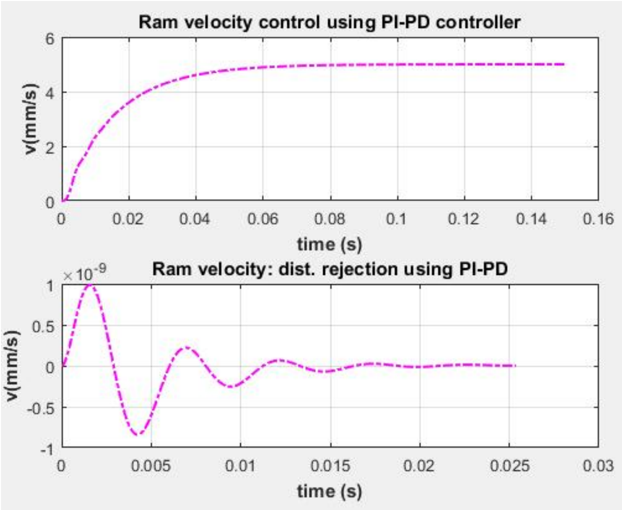

Fig.6 Ram velocity control using a PI-PD controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: 0.0617 s
- Control system characteristics for disturbance rejection:
  - Maximum time response: 0.986×10^{-9} mm/s
  - Minimum time response: -0.84×10^{-9} mm/s
  - Settling time to zero: 0.025 s

VI. CONTROLLING THE STRIP THICKNESS USING A 2DOF 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 tank level [15], liquefied natural gas pressure [27], boost-glide rocket engine [25], BLDC motor [32], second-order process [42], delayed double integrating process [23], boiler drum water level [29], furnace temperature [33], boiler temperature [28], an electro-hydraulic drive [34], cavity gate pressure [17], injection molding machine barrel temperature [35] and mold packing pressure [36].

The block diagram of a control system incorporating a 2DOF structure and the controlled process is shown in Fig.7 [42].

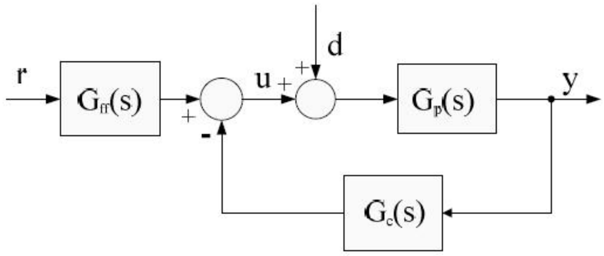

Fig.7 Strip thickness control system using 2DOF-2 controller [42].

The structure of the 2DOF controller varies according to the location of the two elements of the controller and on the structure of each control element inside the 2DOF controller. In version 2 of the 2DOF controller (2DOF-2), the location of the two elements is as shown in Fig.7, the feedforward element is a PI control mode and the feedback element is a PID control mode [34], [35], [36], [42]. Here, in this application of 2DOF controller to control the ram velocity of an injection molding machine, I introduce the third version, 2DOF-3. It is more simple than the second version where both control elements are a PD control mode. It is well known to control engineers and researchers that the PD control mode will produce steady-state error which has to be kept minimum if the accuracy of the control system is one of its objectives. The author accepts this challenge and used the PD control mode and adds a constraint that eliminates completely the steady state error of the closed loop control system in Fig.7 through a specific relation between the proportional gains of the PD control modes and some of the process parameters. The transfer functions of the two elements of the 2DOF-3 controller are given by:

$$G_{ff}(s) = K_{pc1} + K_{d1}s$$

and $$G_c(s) = K_{pc2} + K_{d2}s \qquad (9)$$

Where: K_{pc1} , K_{pc2} are the proportional gains of the two PD control modes.

K_{d1} and K_{d2} are the derivative gains.

The 2DOF-3 controller has four gain parameters to be tuned to provide the required performance of the closed-loop system of the strip thickness control.

- The closed-loop transfer function of the control system incorporating the 2DOF-3 controller is derived from the block diagram in Fig.7 and using the process transfer function in Eq.2 and the controller transfer functions in Eqs.9.
- The controller parameters are tuned using the same procedure presented for the PD-PI and PI-PD controllers. The tuning results are as follows:

$K_{pc1} = 2.054501$, $K_{d1} = 0.001760$

$K_{pc2} = 1.064653$, $K_{d2} = -0.001407$ (10)

- The closed-loop transfer function of the control system for a disturbance input is derived from the block diagram of the control system (Fig.7) with zero reference input.
- The closed-loop transfer functions are used to plot the unit step input step time response of the control system using the '*step*' command of MATLAB as shown in Fig.8.

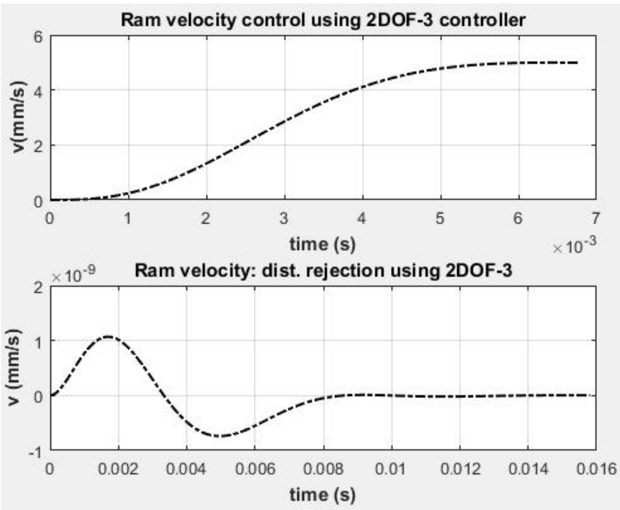

Fig.8 Ram velocity control using a 2DOF-3 controller.

COMMENTS:

- Control system characteristics for reference input tracking:
  - ➢ Maximum percentage overshoot: zero
  - ➢ Settling time: 0.0054 s
- Control system characteristics for disturbance rejection:
  - ➢ Maximum time response: 1.069×10^{-9} mm/s
  - ➢ Minimum time response: -0.74×10^{-9} mm/s
  - ➢ Settling time to zero: 0.014 s

VII. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed controllers, the step time response for reference input is compared with that using an improved PID controller used by Yang et al. to control the same ram velocity [8] and shown in Fig.9.

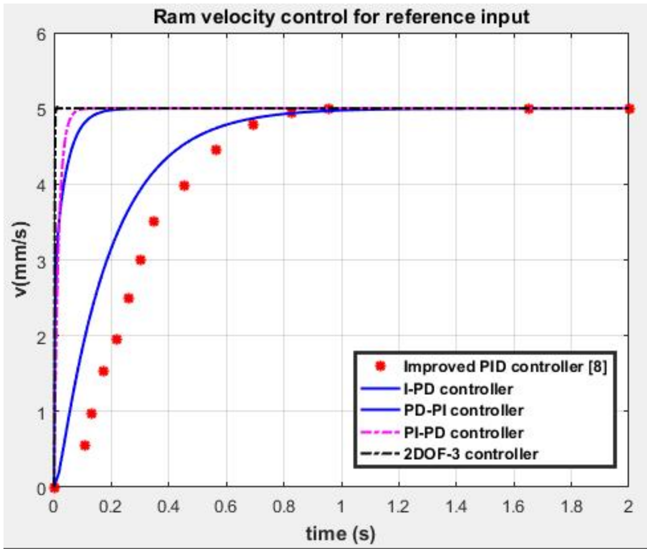

Fig.9 Comparison of reference input tracking step time response.

- For disturbance input, the step time response of the control system representing the disturbance rejection using the proposed four controllers from the second generation of PID controllers is compared and presented in Fig.10.
- A quantitative comparison for the time-based characteristics of the control systems used to control the ram velocity of an injection molding machine is given in Table 1 for a reference step input and table 2 for disturbance rejection.

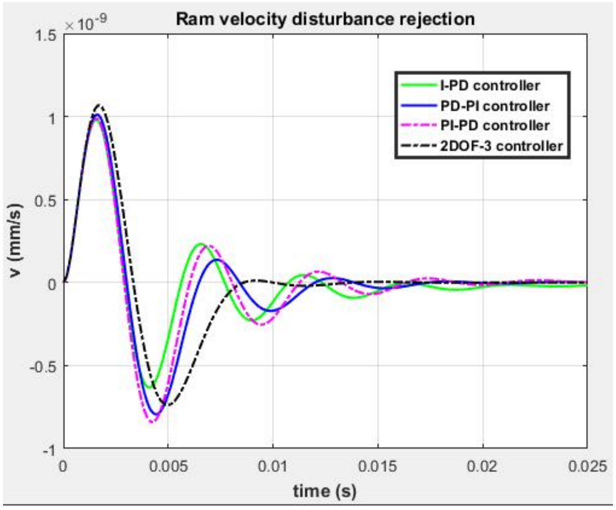

Fig.10 Comparison of disturbance input step time response (disturbance rejection).

TABLE 1
TIME-BASED CHARACTERISTICS OF THE RAM VELOCITY CONTROL SYSTEM FOR REFERENCE INPUT TRACKING

Controller	Improved PID [8]	I-PD	PD-PI	PI-PD	2DOF-3
Maximum overshoot (%)	0	0	0	0	0
Settling time (s)	0.770	0.743	0.135	0.062	0.0054

TABLE 2
TIME-BASED CHARACTERISTICS OF THE DISTURBANCE STEP TIME RESPONSE OF THE RAM VELOCITY

Controller	10^9 Maximum time response (mm/s)	10^9 Minimum time response (mm/s)	Settling time to zero (s)
I-PD	0.980	-0.630	0.030
PD-PI	1.010	-0.790	0.018
PI-PD	0.986	-0.840	0.025
2DOF-3	1.069	-0.740	0.014

VIII. CONCLUSIONS

- This research work investigated the use of I-PD, PD-PI, PI-PD and 2DOF-3 controllers from the second generation of PID controllers to control the ram velocity of an injection molding machine.
- The process under control (ram velocity) is an example of processes with good dynamics it has no overshoot and small settling time and steady-state error.
- The paper proposed four controllers from the second generation controllers presented by the author starting from 2014.
- The performance of the proposed controllers was compared with that of an improved PID controller from a previous research work.
- All the proposed controllers provided excellent control system performance without any overshoot.
- Regarding the settling time of the step response of the control system, the four controllers provided 0.743, 0.135, 0.062 and 0.0054 s for the I-PD, PD-PI, PI-PD and 2DOF-3 controllers respectively compared with 0.77 s for the improved PID controller.
- Even though the 2DOF-3 controller was introduced by the author in this research work it could generate a step time response with zero maximum overshoot and very small settling time representing the best controller among the four presented controller for the ram velocity of the injection molding machine.
- Regarding the disturbance rejection, the four proposed controllers provided very low maximum time response, minimum time response and settling time to zero with using a proper second-order high-pass filter with the disturbance input. This means that the four proposed controllers provide excellent disturbance rejection specially the 2FOF-3 controller.

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DEDICATION

GAMAL ABDULAZIZ AHMED

- Professor of Arabic Language and its Sciences.
- Taught Arabic Language and its Sciences in Collage of Sharia Sciences of Sultanate Oman, King Khalid University of Saudi Arabia and in the Faculty of Dar Al-Ulum of Cairo University.
- He is the author of more than 60 books on all sciences of the Arabic Language.
- He wrote about 11 research papers in scientific journals.
- He wrote about 2000 articles in Egyptian, Gulf and European newspapers.
- He is a truly lover to Egypt and to any researcher who works seriously with dedication to raise the name of his beloved Egypt in the international domain.
- In the last few months, Dr. Gamal didn't miss any one of my published papers with intensive comments and encouragements for sake of its reputation among the international well known universities.
- Thanks Professor for your love to Egypt and for your time given to follow up research carrying its name.
- I am happy to dedicate this research work to you.

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.
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- Honourable Chief Editor of the International Journal of Computer Techniques.
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