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INJECTION VELOCITY CONTROL BASED-ON AN ITERATIVE LEARNING AND FEEDBACK COMBINED CONTROLLER

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Abstract: Injection velocity is a key variable in injection molding process. The dynamics of injection velocity is largely affected by the control valves used in the hydraulic system. Previously, it has been controlled precisely using advanced control algorithms based on servo-valves. However, this increased significantly the capital and maintenance costs. In this paper, the injection velocity was controlled using economical but slow response proportional valves. Iterative learning control is adopted to exploit the repetitive nature of the process for control performance improvement with the slow valves. Most nonlinearity is handled by the ILC control, with a simple feedback control incorporated to provide within-cycle disturbance rejection. Experiments show that the proposed method can work well over a wide range of operating conditions.

Keywords: Injection moulding, iterative methods, feedback control, nonlinear systems, control valves.

1. INTRODUCTION

Injection molding, a major polymer processing technique, is a typical multi-stage batch process consists of filling, packing-holding and cooling three main stages. Filling is the first stage of the molding. During filling, the polymer melt is forced into a mold cavity through the nozzle and runner system by a screw forward motion until the mold cavity is completely filled. The nature of the melt flow entering the cavity influences strongly the quality of the molded part, particularly the mechanical properties, such as tensile strength, impact strength and dimension stability. Polymer flow rate inside the mold cavity is not directly controlled due to the lack of a practical measurement. It is common to control melt pressure or ram injection velocity in filling stage, as they can be correlated well to the filling rate.

Ram injection velocity, often referred simply as injection velocity, approximates but not equal to the polymer filling rate entering a mold cavity due to the melt compressibility and the plastic leakage through the check ring valve. Despite the fact that injection velocity differs from the polymer filling rate, it is still widely used as a controlled variable during injection phase, as it provides a better approximation than the other variables such as cavity pressure or nozzle pressure. A proper setting and good control of injection velocity can achieve an evenly distributed flow pattern, avoid over-pressurization, high thermal stresses, and high residual flow stresses (Boldizar *et al.*, 1990).

Like any process control, a dynamic model is required for the injection velocity control. The modelling of injection velocity based on servo-valve controlled hydraulic systems has been studied by Davis (1976), Abu Fara (1984) and Wang *et al.* (1985).

Pandelidis and Agrawal (1987, 1988) conducted a series of control simulations for injection velocity control. Their simulation results using a self-tuning controller showed a better control performance than a traditional PID controller. However, none of their work was tested experimentally. The non-linear and time-varying characteristics of the injection velocity during the filling phase were ignored.

Extensive experimental control applications have been conducted by Gao's group. A model-free fuzzy controller was first designed by Tsoi and Gao (1999) for injection velocity control. Non-linear and time-varying characteristics of the velocity were reported. The controller rules were determined by a phase plane analysis. The controller was tested and found to work reasonably well under different molding conditions. However, this design requires the user to have extensive experience with the process, which may be not available in certain cases. Later, Yang and Gao (1999, 2000)

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adopted an adaptive self-tuning scheme for injection velocity control which includes a process model, an online model identification module and a feedback controller. They first implemented a pole-placement design as the feedback controller. Good experimental control results have been achieved for a wide range of operating conditions by incorporating some enhancements such as adaptive feedforward control and cycle-to-cycle learning. They improved the robustness of this adaptive self-tuning regulator by introducing a generalized predictive control (GPC) design. The adaptive GPC controller not only has an inherent good performance on set point tracking, but also exhibits good robustness against model mismatch. Further improvement has been focused on the process model (Li *et al.*, 2001). A fuzzy multi-model has been proposed and implemented for the injection velocity control with good experimental results.

In all the above works, the velocity control was based on servo-valves. In the current molding industry, there are two types of commonly used control valves providing directional and flow control of the hydraulic system, i.e. the servo-valve and proportional valve. A servo-valve is a device, which converts a low power electrical input signal into a proportionally higher hydraulic output with high accuracy. Servo-valve normally has complicated structure including a torque motor, a flapper valve, a spool valve for the second hydraulic stage, and an internal feedback mechanism (Rohner, 1995). Using servo-valve as the actuator for the closed-loop control produces a good control performance with fast response. However, it not only increases the capital cost but also operation cost, for example, it requires a much more sophisticated oil filtration system. The proportional valve is another type of control valves developed to fill the wide gap between simple on/off valves and sophisticated servo-valves. Corresponding to the control signal, its proportional solenoid produces a proportional spool shift for flow controls. The proportional valves have simpler structures and are much less expensive than the servo-valves. It also has good tolerance of small oil contamination. For these reasons, they are widely used in molding industry. Compared to the servo-valve, the disadvantages of the proportional valve are obvious. It has a relatively slower response, resulting in a large time constant of the hydraulic system. The input-output linearity of proportional valves is also not as good as that of the servo-valve, and severe nonlinear behavior can be observed especially during the transient stages.

In summary, though many research efforts have been put on the injection velocity control, they were mostly based on the fast response servo-valves. In practice, when slow response proportional valves are adopted to control the injection velocity, the performance is deteriorated significantly. The objective of this paper is to develop a practical robust control scheme for injection velocity using proportional valves, taking the repetitive nature of the injection molding process into account.

2. CONTROL BACKGROUND

Injection molding is a cyclic process typically lasts for several seconds to minutes. The control of such a batch process, unlike that of the continuous processes, involves keeping a defined sequence of operations. At the same time, the control system must also control the key process variables to follow certain profiles repetitively and accurately to ensure a good part quality. The disturbances can come from the materials being processed, molding machine itself, environments and human interferences. Most disturbances cause the process to drift slowly over cycles instead of abrupt changes. For example, mold temperature may increase from cycle to cycle during the warm-up stage as a result of the continuous molding operation. These disturbances are typically difficult to be accurately represented by mathematical models, but their impacts on the control system can be reflected by the change of the manipulated variables. Injection molding is a repetitive process, information of past controls may be explored for improvement of the current and future cycles. Iterative learning control, a control algorithm taking advantage of the repetitive nature of the process, can deal with the nonlinear properties of the process and slow response of the actuators therefore is a good candidate to control the injection velocity.

Iterative learning control is motivated to mimic human learning process. It is originally developed for the manipulation of industrial robots, in which it is required to repeat a given task with high precision. By using the repetitive nature of the processes, ILC progressively and iteratively improves the control accuracy along two time dimensions for control input, that is the trial (or batch) direction from trial to trial, and the elapsed time direction during a trial from step to step. This two-dimensional learning results in advantages over the conventional feedback control techniques where only one time dimensional control actions are made along the time axis. The key for a learning control design is to find an algorithm to ensure that the control input is generated for next trial in such a way that the performance is improved for each successive trial. The concept of iterative learning for generating such an input was first introduced by Uchiyama (1978) and was later mathematically formulated by Arimoto *et al.* (1984). Since then, considerable efforts have been made on the development and analysis of iterative learning control. Recently, ILC has been applied to some repetitive processes, such as batch reactor (Lee *et al.*, 1996), batch distillation, and injection molding (Havlicsek *et al.*, 1999).

The conventional ILC scheme works as an open-loop feed-forward compensator. It generates the control signals of the future cycle u_{k+1} by using the input, output, and the desired trajectory of the current cycle, u_k , y_k and r , respectively. Over past a few decades ILC has made a good advance, most practical research has focused on the P-type, D-type and modified PD-type or PID-type learning algorithms. These learning have good physical insight, and they are relatively easy to be implemented. It has been found, however, that an ILC not using within cycle feedback tends to be sensitive to perturbation, and tends to be slow in system convergence (Bien *et al.*, 1998). Feedback combination is thus considered in this paper.

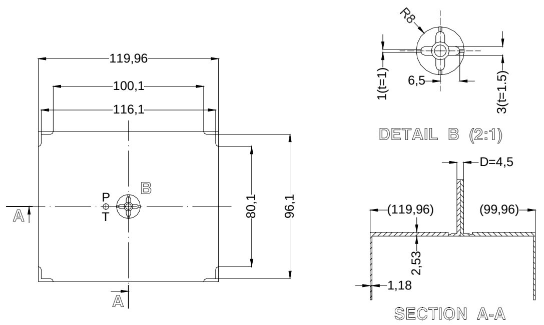
A simple but effective P-type iterative learning algorithm is adopted in this paper to control the injection velocity. It updates the control signal of the complete injection stage $[0, \ N]$ for the next cycle based on the error profile of the current cycle, as shown below:

$$u_{k+1}(t) = u_k(t) + L_p e_k(t) \qquad (1)$$

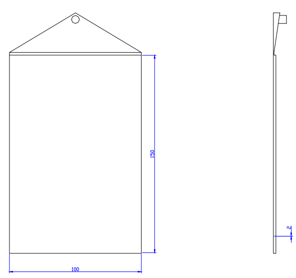
where $e_k(t) = r(t) - y_k(t)$ is the tracking error of current cycle k, and L_p is the learning rate.

3. EXPERIMENTAL SETUP

The molding machine used is a Chen-Hsong reciprocating screw injection molding machine, model JM88MKIII. The maximum machine clamping force is 88 ton, and the maximum shot weight is 128 g. A Temposonics series III displacement/velocity transducer, type RH-N-0200M, is installed to measure the injection displacement and velocity. The hydraulic system is fitted with two Bosch proportional valves, type PV-60 and QV45-RGC1, to control the hydraulic pressure and flow rate, respectively. An industrial PC was used as the control platform for the control of the injection molding machine. Two National Instruments data acquisition cards mounted in the PC are used to provide interface to the molding machine. All the programs are developed using C language under a real-time multi-task operating system, the QNX. There are two molds used in the experiments, as shown in Figure 1.



(a) Mold 1 geometry



(b) Mold 2 geometry

Figure 1: Geometry of molds used in injection molding experiments.

All the experiments were conducted using material of high-density polyethylene (HDPE) unless otherwise specified.

4. RESULTS & DISCUSSIONS

4.1 Open loop tests

Some open loop experiments were conducted first for the observation of the dynamic characteristics of injection velocity, with a sampling rate of 5 millisecond. The Mold 1 shown in Figure 1(a) was used first with the proportional valve opening step-up change from 42% to 48% at 600ms of injection time. The results are shown in Figure 2(a) where dot line shows the valve opening and the solid line indicates the corresponding injection velocity response. It is obvious that the injection velocity exhibits large over-shoot in the initial stage of filling. When a valve opening step change was applied, the injection velocity has a relatively slow response with large over-shoot. The nonlinear response of the injection velocity is mainly due to the hydraulic system and complicated rheological properties of the polymer melt. The nonlinear and time-varying characteristics of injection velocity have been analyzed extensively in References (Tsoi *et al.*, 1999 and Yang *et al.*, 2000). With the replacement of the control actuators from the servo-valves to proportional valves, the nonlinearity has become even severe.

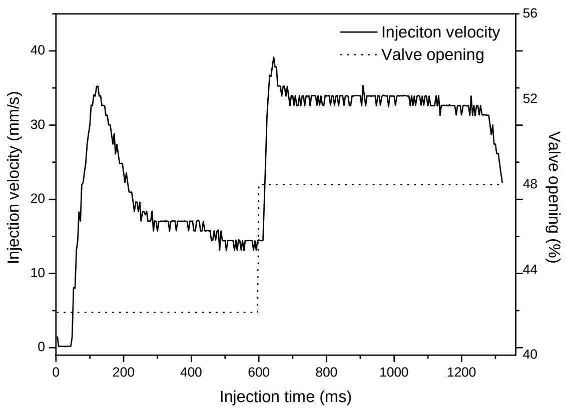
Another open loop experiment was conducted using the Mold 2 shown in Figure 1(b). The results are plotted in Figure 2(b). A constant valve opening of 60%, significantly larger than the opening used in Mold 1, has been applied, as indicated by the dot line in Figure 2(b). The corresponding injection velocity response, as shown by the solid line, is significantly different from that of Mold 1. This result not only proves the nonlinear characteristics but also shows that the injection velocity dynamics changes significantly with different molds used in the experiments.

4.2 Determination of delay and sampling rate

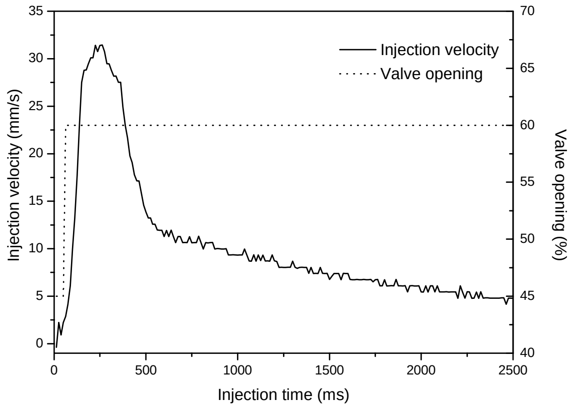
A P-type learning algorithm has been selected to control the injection velocity in this paper, as formulated in Equation (1). The advantage of using P-type learning is that it is a simple and effective ILC method, and the design of P-type learning does not require any process model, hence be beneficial to industrial implementation.
However, Equation (1) cannot be applied to injection velocity control directly, due to the process delay. It must be modified to take the delay into consideration, as shown in the following:

$$u_{k+1}(t) = u_k(t) + L_p e_k(t + t_d) \qquad (2)$$

where t_d is the time delay of injection velocity. It has been observed that the order of t_d is important for the successful implementation of ILC. A delay mismatch may cause the accumulation of control errors and results in an oscillatory control after several cycles. It is therefore decided to use the open loop velocity response to identify the delay orders first.



(a) Mold 1 open loop test



(b) Mold 2 open loop test

Figure 2: Open loop injection velocity response of two molds

The injection velocity response to the process input, the proportional valve opening, is represented by a discrete z-transform equation:

$$A(z)y(t) = B(z)u(t - n_d) + e(t) \quad (3)$$

where y is the velocity output, u is the control action (the proportional valve opening), and:

$$A(z) = 1 + a_1 z^{-1} + ... + a_{na} z^{-na},$$

$$B(z) = (b_0 + b_1 z^{-1} + ... + b_{nb-1} z^{-nb+1}) \cdot z^{-nd} \quad (4)$$

Na and nb are the orders of A and B polynomials, nd represents the delay order of the process. Equation 3 is the velocity model in AutoRegressive with eXternal input (ARX) form. The open loop response of Mold 1 was used for the model identification. To identify the delay order accurately, this open loop response was fitted into the ARX model with same na and nb values but different delay order. The na and nb were determined both to be 3, as the process is unlikely to be a higher order system. The model prediction loss function as well as the Akaike's Final Predictive Errors (FPE) are used to determine the degree of model matching (Ljung, 1987). The resulted loss functions and FPE values with respect to different delay orders are plotted in Figure 3. It is clearly shown that the prediction reaches its best performance when nd=5, i.e. 25 millisecond. The sampling rate is thus decided to be 12.5, half of the process delay.

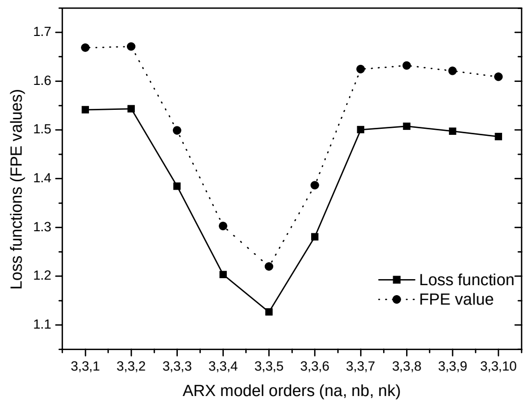


Figure 3: Determination of delay orders using loss functions and FPE values

4.3 Incorporation of feedback control

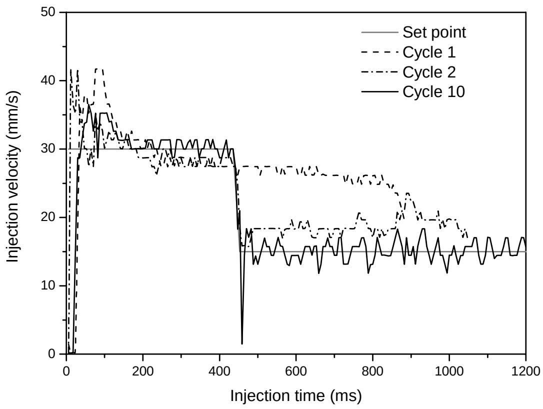
The ILC law as formulated by Equation (2) was thus implemented to control injection velocity with a sampling rate of 12.5 ms, and delay order of 2. The learning rate is determined to be 0.025 through inversion of the process gain. The experimental results with Mold 1 and material of HDPE are shown in Figure 4, where Figure 4a plots the injection velocity measurements and Figure 4b plots the corresponding proportional valve opening. A step down velocity profile was selected, as shown by the solid gray line in Figure 4a. The first cycle, as indicated by the dash line, was open loop controlled with an arbitrary constant valve opening of 46%. The second cycle's injection velocity, shown by the dash-dot line, quickly approaches to the set point. The velocity response of the 10^{th} cycle, plotted by the solid line, is very close to the set point profile. The control results prove the learning capability of ILC scheme. Notice that the valve opening was adjusted before the set point step change, thus the injection velocity can follow the set point profile closely without delay. This observation shows the inherent advantage of ILC. However, there are several problems in this result. First the initial stage control is still oscillatory and steady state noisy result is still obvious. These problems are mainly due to the lack of within cycle feedback control. It has been reported that ILC without feedback action tends to be susceptible to the process noise and hence to be unstable. Therefore, a simple integral feedback control is added to the original ILC to enhance the noise rejection capability of the velocity controller and eliminate the steady-state errors. The ILC incorporated with the I-type feedback control can be written as follows,

$$u_k(t) = u_{k-ff}(t) + u_{k-fb}(t) \quad (5)$$

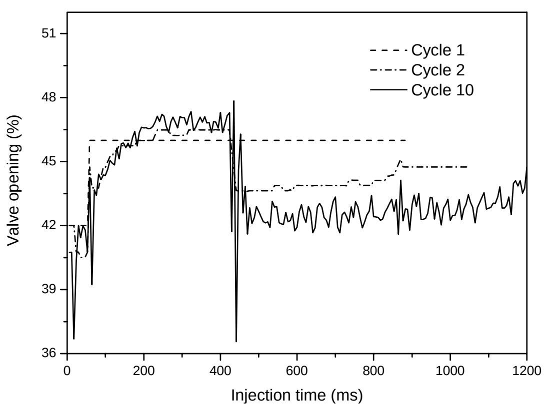
where $u_{k-ff}(t)$ is the feedforward or learning control action calculated using Equation (2) and $u_{k-fb}(t)$ is the feedback control action calculated as below,

$$u_{k-fb}(t) = u_{k-fb}(t-1) + k_i \cdot e_k(t) \quad (6)$$

The proportional control gain ki is tuned using trial and error method, and determined to be 0.005.



(a) Injection velocity measurements



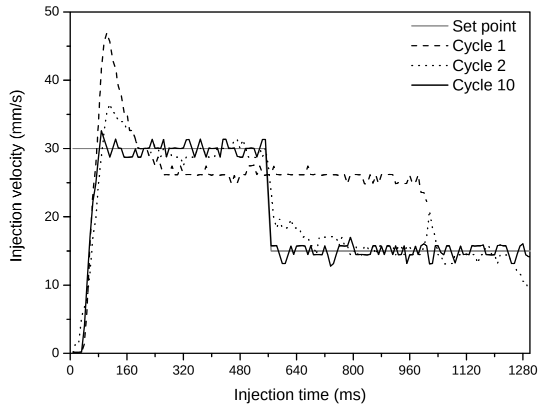
(b) Corresponding valve opening

Figure 4: Injection velocity iterative learning control without feedback enhancement

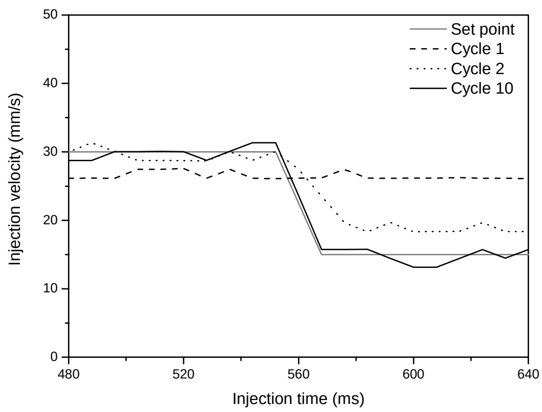
The control results with ILC and I-type feedback control are shown in Figure 5. The injection velocity measurements are shown in Figure 5a, and zoomed-in plot around the set point step change is shown in Figure 5b. All the other experimental conditions are the same as previous. Due to space limitation, the corresponding valve openings are not shown in this paper. It is clearly shown that with the incorporation of the feedback control, the control performance is improved throughout the filling stage and the steady state responses are smoother than before. It is also clearly shown in Figure 5b that in the 10^{th} cycle the set point step change has been closely followed, despite the slow response of the proportional valves.

4.4 Different operation conditions

The designed ILC controller with I-type feedback has been tested with different operating conditions to evaluate the control performance. As the injection velocity varies significantly with mold geometry, a different mold, Mold 2, was tested first. The injection velocity control results are shown in Figure 6. The valve opening of the first cycle was arbitrarily set to be 60%. It is shown in Figure 6 that although the control converges to the constant set point value eventually, i.e. after 17 cycles, the convergence rate is too slow. This slow convergence rate is undesirable in industry. There are mainly two methods to speed up the convergence, to increase the learning rate, or to improve the first cycle's control performance. A conservative PI controller was tuned to control the injection velocity in the first cycle, and the same learning rate was used for the rest of cycles. The control results are shown in Figure 7. This time the control only takes about 5 cycles to converge, hence proves the effectiveness of this improvement.



(a) Injection velocity measurements



(b) Zoomed-in plot around step change

Figure 5: Injection velocity iterative learning control with feedback enhancement

Different material, namely polypropylene (PP) was also tested experimentally. The injection velocity control results using PP were shown in Figure 8. The control quickly converges to the set point, which is a step down profile. The 10^{th} cycle's injection velocity measurement is the fastest response without overshoot and it almost overlaps with the set point despite the slow response of the proportional valves, indicating the good performance of the control system.

5. CONCLUSIONS

An iterative learning control system has been adopted in this paper to control the injection velocity. Open loop tests have demonstrated the nonlinearity and slow response of the velocity dynamics. By proper selection of the sampling time and delay order, the ILC, enhanced with an integral feedback control, can effectively control the injection velocity. The designed system has been experimentally tested to work well for a wide range of operating conditions.

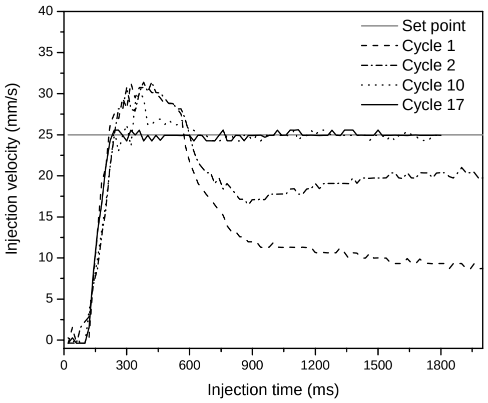


Figure 6: Injection velocity iterative learning control using Mold 2, 1st cycle opening loop control

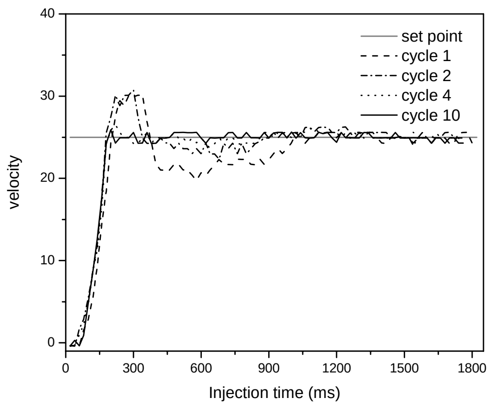


Figure 7: Injection velocity iterative learning control using Mold 2, 1st cycle closed-loop control

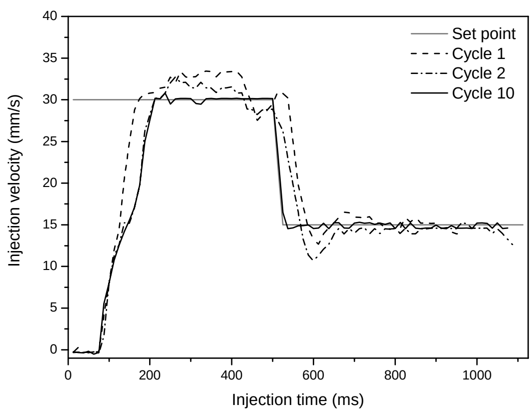


Figure 8: Injection velocity iterative learning control using PP

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