This article can be cited as S. John and J. O. Pedro, Neural Network-Based Adaptive Feedback Linearization Control of Antilock Braking System, International Journal of Artificial Intelligence, vol. 10, no. S13, pp. 21-40, 2013.

Fuzzy Sliding Mode Control for Enhancing Injection Velocity Performance in Injection Molding Machine

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ABSTRACT

In this study, injection velocity in injection molding process was analyzed. Since physical behavior of thermoplastic and environmental condition in injection machine such as high temperature and pressure make a complex dynamics in injection molding system, the injection velocity is consequently difficult to control by some classical control methods. Hence, robust and adaptive control (Fuzzy Sliding Mode Control) was proposed to control the injection velocity in finite time. In this control strategy, sliding mode control intended to overcome system dynamics, while Fuzzy controller would decrease both output error and chattering phenomena due to sliding mode process. The simulation results showed that proposed control could decrease chattering phenomena and followed velocity set point with small error. The two cycles of set point were also presented to examine controller's robustness. In future, this proposed control can be potentially applied in real system.

Keywords: Injection velocity, injection molding, fuzzy control, sliding mode control, fuzzy sliding mode control.

Mathematics Subject Classification: 93C40, 93C42

1. INTRODUCTION

Injection molding is one of the most important processes in plastics industry. It is a highly accurate and inexpensive method for mass producing lightweight, and complex-shaped three-dimensional plastic products (Kuo and Su, 2007). In injection molding processes, several studies have revealed that setting of processing parameters such as mold temperature, melt temperature, injection velocity, and packing pressure, caused a shrinkage, flashing and residual stress which then affected the overall qualities (Kuo and Su, 2007; Sha et al., 2007; Huang et al.,2009; Kalima et al., 2007). Hence, the study of control and setting of processing parameters are very important in plastic industry. For example the injection velocity, it has significant effect to influence common problems such as flashing and short shots (Dubay et al., 2007). Plastic engineers usually used a velocity profiling to achieve a constant melt flow front velocity which then affected molecular orientation and internal stresses produced in molded parts (Agrawal et al., 1987). Another study confirmed that a significant improvement in the overall qualities of plastics products could be derived by an accurate and tight closed loop control of injection velocity (Rosato and Rosato, 2000).

As depicted in Fig. 1, a typical velocity profile has several sections according to phase being processed (Agrawal, and Pandelidis, 1988). In section I, the velocity is very fast and then held constant. This profile is aimed to minimize injection time and heat loss in the material. During section II, the velocity is rapidly reduced to eliminate jetting at the gate. Once the melt enters the cavity, the aim is to maintain a constant flow front speed. The ram velocity should increase to maintain constant velocity of the melt across the mold surface during section III, while the velocity should be maintained at a constant during section IV. The velocity is then reduced during section V to eliminate flashing and/ or over-packing.

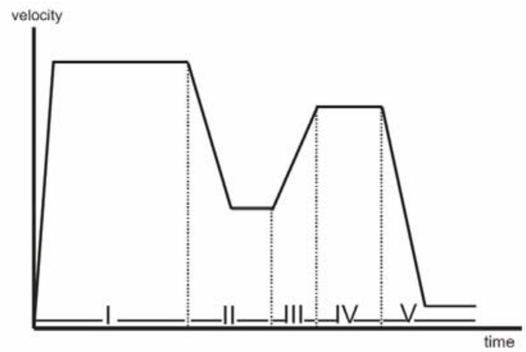


Figure 1. The typical velocity profile.

Many control methods have been applied in each specific section of injection molding process. The control methods were different one to another due to the variation of plastic material, mold geometry, and complexity of products. For injection velocity control, several control methods have been proposed to overcome specific control problems, for instances, high speed-finite time in CD/ DVD manufacturing, robustness of control method to follow multi cycles of desired trajectories, and consistency of control for different materials, mold, and processing parameters. Tsoi and Gao (Tsoi and Gao, 1999) proposed fuzzy logic to control injection velocity, which was then confirmed with several different processing parameters, molds and materials. Fuzzy logic was also employed to maintain plant input due to change of velocity set point. The proposed control was successfully implemented with different molds, materials, barrel temperatures, and injection velocity profiles. Huang et al. (Huang et al., 2004) proposed predictive learning control method to make robust control against system uncertainties. In their control system, neural network was used to find biased function which was then added to feedback control. Simulation was conducted to achieve their claim. In (Lin and Lian, 2010), Lin and Lian proposed self-organizing fuzzy controller by changing control structure to be closed-loop. In their study, the proposed control could learn from current process and update the fuzzy rule. Thus injection molding machine did not need to be modeled. However, all results in the above papers were in low velocity and some complexities have not been addressed. Hence, those methods are insufficient due to current manufacture challenge. A high technology manufacture such as LCD and DVD needs high speed injection in short time. In (Gao et al., 2001), Gao, Yang, and Shao proposed robust iterative learning method to control middle-speed injection velocity. The proposed controls were also concerned to stability and robustness issues. However, velocity profile and time cycle have not been addressed at real condition of injection molding process.

In this study, the authors extended the work of Feriyonika and Gunawan. (Feriyonika and Gunawan, 2011). Unlike previous work that used Fuzzy sliding mode control to follow one cycle of velocity set point, this study used the controller to follow two cycles of velocity set point so that the controller's robustness could be more evaluated. Another different thing is disturbance representation, which was not only represented by adding uniform signal but also by adding white noise. For control strategy, sliding mode control intended to overcome system dynamics, while Fuzzy controller would decrease both output error and chattering phenomena due to sliding mode process.

2. FUZZY CONTROLLER AND SLIDING MODE CONTROL

2.1 Fuzzy controller

Fuzzy control is a control method based on Fuzzy logic, a new concept in set theory which uses membership grade for an element of a set. Unlike classical set where an element has only two possibilities: 0 or 1, in Fuzzy set, an element will have membership grade from 0 to 1 (Kusumadewi, 2005). Nowadays, Fuzzy logic has been used in many applications such as washing machines, microwave ovens, rice cooker, elevator, train, automotive, medical diagnosis, security, data compression, etc (Reznik, 1997). Fuzzy controller has several control schemes based on cases being faced: direct control, feedforward control, and parameter adaptive control (illustrated in Fig. 2) (Jantzen, 1998). For direct control, as shown in Fig. 2(a), the Fuzzy controller is laid in forward path of feedback control scheme. In this structure, if the output of process is different with the reference, the controller will evaluate based on control strategy (Jantzen, 2007). In feedforward control, as shown in Fig 2(b), Fuzzy will work as compensator for measurable disturbance. In this scheme, linear controller (C) such as PID and non linear controller such as Fuzzy are collaborated (Reznik, 1997). The last scheme is Fuzzy logic for parameter adaptive controller. As shown in Fig. 2(c), Fuzzy will tune the parameter of main controller according to each operating point.

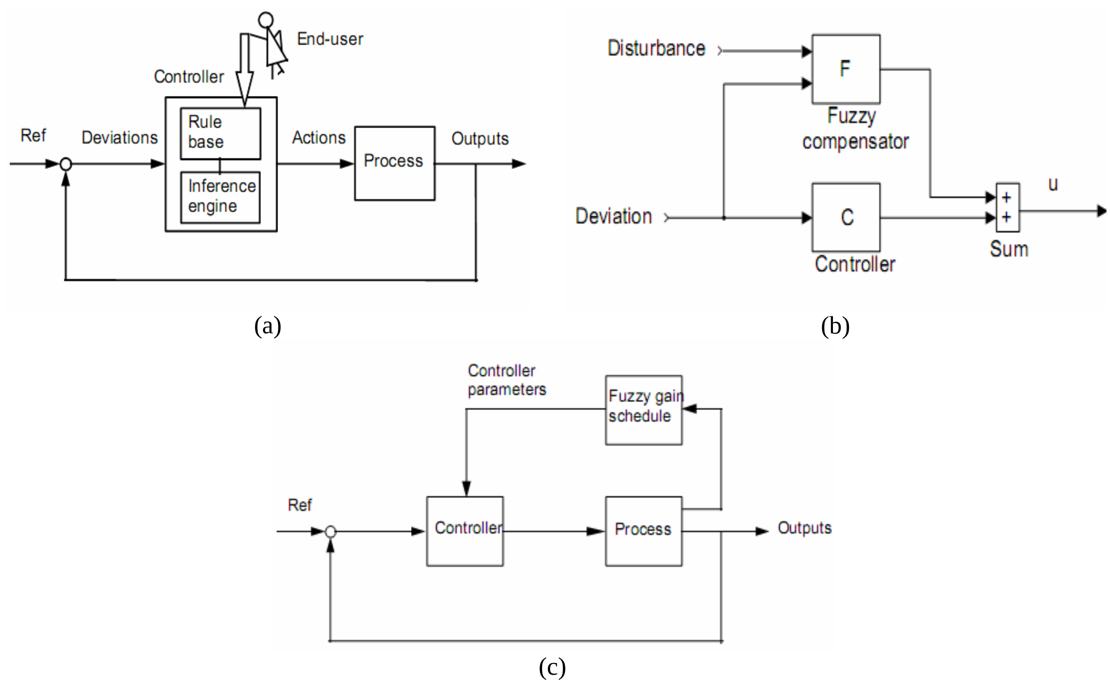


Figure 2. Control schemes (Jantzen, 1998). (a). Direct control. (b). Feedforward control. (c). Parameter adaptive controller.

The structure of Fuzzy controller, as shown in Fig. 3, consists of three main parts: preprocessing, Fuzzy controller, and postprocessing (Jantzen, 1998). In the first block, preprocessing process is employed to change the input of controller which is often in hard or crisp form. Several commonly used methods are quantization, filtering, normalization or scaling, averaging, integration and differentiation. The next process is fuzzification, which is the first block inside controller part. This process intends to convert the data to degree of membership function such as triangle and trapezium. The Fuzzy data are then processed based on condition and conclusion rule. Popular Fuzzy rule processors are Mamdani type, linguistic variables, Fuzzy rule firing, calculating the applicability degree, clipping and scaling, Takagi, and Sugeno type (Reznik, 1997). The results of rule processing are subsequently changed to crisp value by defuzzification process. Finally, the postprocessing is needed to change the Fuzzy's output to engineering unit such as volt, current, meter, etc. These fuzzy controllers have been very widely implemented in many areas, such as: continuously variable transmission, electromagnetically actuated clutch, magnetic levitation system, and generalized van der Pol oscillator (Dragos et al., 2012; Precup et al., 2011)

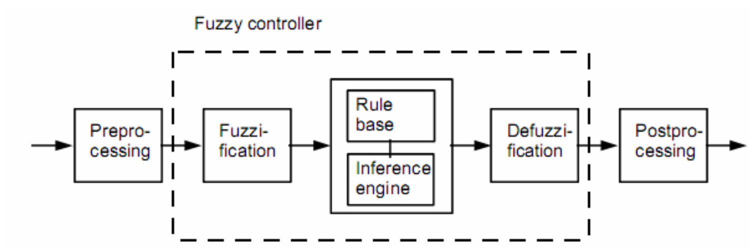


Figure 3. Structure of Fuzzy controller (Jantzen, 1998).

2.2 Sliding mode control

Sliding mode control is fundamentally a consequence of discontinuous control. It was found when oscillations appearing in bang-bang control was tried to solve (Perruquetti and Barbot, 2002). This control method pushes all states of system to reach a sliding surface and follow the surface line to reach equilibrium point in finite time. The main parts of sliding mode control design are: designing sliding surface and input manipulation so that the response is forced to move along surface, thus producing sliding mode. The surface and characteristic equation of sliding mode control are stated in Eq. (1) and (2), respectively.

$$\sigma(x) = C_1 X_1 + C_2 X_2 + ... + X_n = 0 \tag{1}$$

$$S^{n-1} + C_{n-1} S^{n-2} + C_{n-2} S^{n-3} + ... + C_2 S + C_1 = 0 \tag{2}$$

Details of sliding mode control designs are presented in following discussions.
Supposed second order system with two states, X_1 and X_2, (Eq. (3) and (4)) (Hung, 2011).

$$\bar{X}_1 = X_2 \, , \tag{3}$$

$$\bar{X}_2 = -a_1 X_1 - a_2 X_2 + b(u + \delta(x,t)) \tag{4}$$

In here, $\delta(x,t)$ is a symbol of disturbances, uncertainty, noises and nonlinearity.

Based on Eq. (1), choose switching surface so that Eq. (5) and (6) are derived. To make the system a stable dynamic, based on Eq. (2), choose $C_1 > 0$.

$$\sigma(x) = C_1 X_1 + X_2 = 0 \tag{5}$$

$$\dot{\sigma}(x) = C_1 \dot{X}_1 + \dot{X}_2 = C_1 X_2 - a_1 X_1 - a_2 X_2 + b(u + \delta(x,t)) = 0 \tag{6}$$

A Lyapunov candidate is then applied to evaluate the stability,

$$\begin{aligned} V &= \frac{1}{2}\sigma^2 \\ \dot{V} &= \sigma \dot{\sigma} \end{aligned} \tag{7}$$

$\dot{V}$ is negative definite if

$$\dot{\sigma}(x) \begin{cases} < 0 \ \text{for} \quad \sigma(x) > 0 \rightarrow \dot{\sigma}(x) < 0 \\ = 0 \qquad \text{for} \qquad \sigma(x) = 0 \\ > 0 \ \text{for} \quad \sigma(x) < 0 \rightarrow \dot{\sigma}(x) > 0 \end{cases} \tag{8}$$

Stability is reached if $\sigma \dot{\sigma} < 0$. Based on the Lyapunov theory, if the sliding surface reaching condition ($\sigma \dot{\sigma} < 0$) is satisfied, the system states will converge to the origin of the phase plane by choosing an appropriate control input u . Fig. 4 describes both reaching and sliding mode processes.

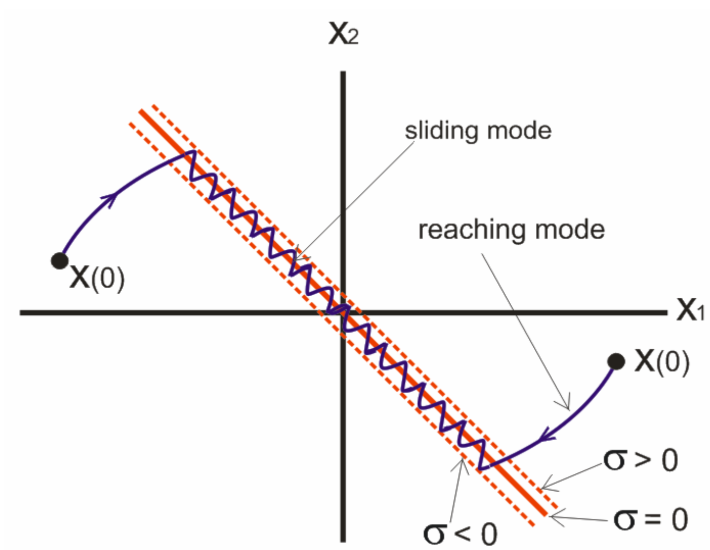


Figure 4. Reaching and sliding mode process (Hung, 2011).

3. CONTROLLER DESIGN

Block diagram of control scheme is depicted in Fig. 5 (Feriyonika and Gunawan, 2011). In this study, the control scheme aims to follow injection velocity profile as close as possible. As shown in Fig 6, one and two cycle of velocity profiles were used as set point. The fourth order transfer function (Wang, 1984) which has been utilized in several papers (Agrawal and Pandelidis, 1988; Huang et al., 2004), Eq. (9), was used as plant model. In control part, sliding mode control used states of the plant to stabilize system dynamics, while Fuzzy controller was employed to rule both switching function and input correction. Details of controller parts will be discussed in following subsection.

$$G(s) = \frac{C(s)}{M(s)} = \frac{2.144x10^{11}}{(s+125)(s+1138)[(s+383)^2+(1138)^2]} \tag{9}$$

Where,

M : manipulated variable, voltage signal to the servo-valve,

C : controlled variable, the ram velocity during injection.

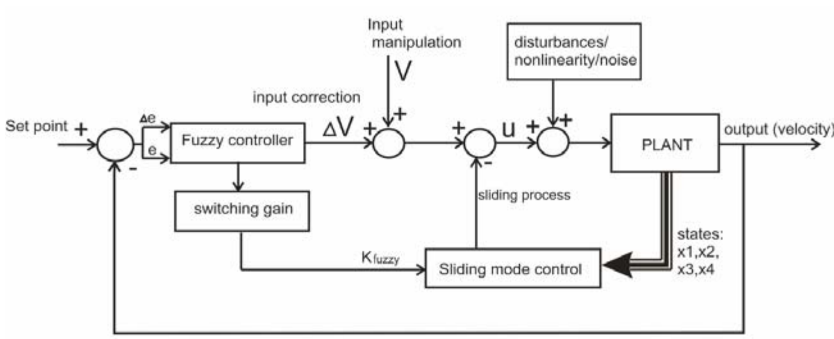
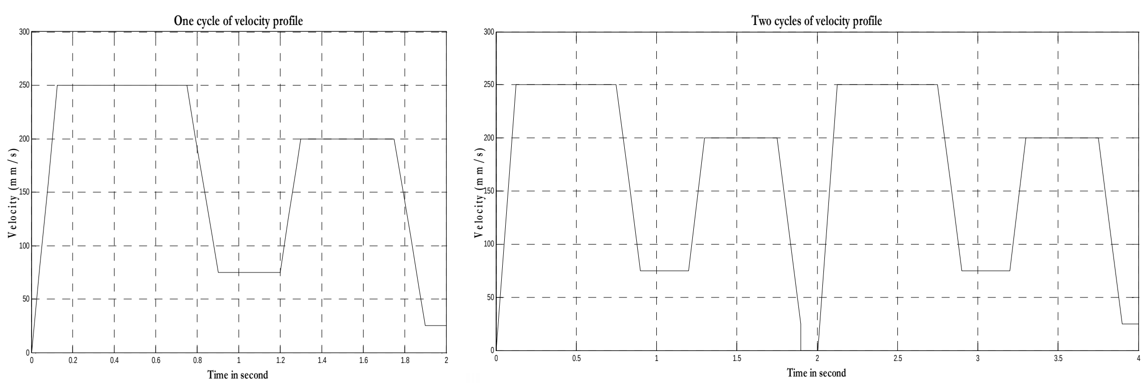


Figure 5. Block diagram of controller scheme.



(a) (b)

Figure 6. Profile of injection velocity. (a). One cycle set point. (b). Two cycles set point.

3.1 Sliding mode control

This controller was employed to stabilize the system dynamics in injection molding process. The plant model, Eq. (9), was firstly changed to state space model in canonical form, Eq. (10), so that state variable equations, Eq. (11) and (12), could be derived.

$$\overline{X} = AX + BU$$
$$Y = CX + DU \tag{10}$$

$$\begin{bmatrix} \underline{X_1} \\ \underline{X_2} \\ \underline{X_3} \\ X_4 \end{bmatrix} = \begin{bmatrix} -2.0290e3 & -2.5446e6 & -1.9213e9 & -2.0412e11 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} [U + \delta(x,t)] \tag{11}$$

$$Y = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} \tag{12}$$

Surface equation was then established by referring Eq. (5) and (6) so that surface equation, Eq. (13), and its characteristic, Eq. (14), were derived.

$$\sigma(x) = C_1 X_4 + C_2 X_3 + C_3 X_2 + X_1 = 0 \tag{13}$$

$$S^3 + C_3 S^2 + C_2 S + C_1 = 0 \tag{14}$$

The value of C_1, C_2, and C_3 were derived by placing all poles to negative region.

$$(s+1000)(s+1000)(s+1000) = 0$$
$$s^3 + 3000s^2 + 3x10^6 s + 10^9 = 0$$

By referring Eq. (14), the values of coefficients are 10^9, $3x10^6$, 3000 for C_1, C_2, and C_3, respectively. These values were then substituted to Eq. (13) so that the surface equation, Eq. (15), was derived. Lyapunov candidate, Eq. (7), was subsequently applied to evaluate the stability. As shown in Eq. (16), the input appears in sliding mechanism.

$$\sigma(x) = 10^9 X_4 + 3x10^6 X_3 + 3000 X_2 + X_1 = 0$$
$$\sigma(x) = 10^9 X_4 + 3x10^6 \overset{(1)}{X}_4 + 3000 \overset{(2)}{X}_4 + \overset{(3)}{X}_4 = 0 \tag{15}$$

$$\sigma \bar{\sigma} < 0$$

$$\sigma(10^9 \overset{(1)}{X}_4 + 3x10^6 \overset{(2)}{X}_4 + 3000 \overset{(3)}{X}_4 + \overset{(4)}{X}_4) < 0$$

$$\sigma(10^9 X_3 + 3x10^6 X_2 + 3000 X_1 + \bar{X}_1) < 0$$

$$\sigma(10^9 X_3 + 3x10^6 X_2 + 3000 X_1 + [-2.029e3 X_1 - 2.5446e6 X_2 - 1.9213e9 X_3 - 2.0412e11 X_4 + U + \delta(x,t)]) < 0$$

$$\sigma(971X_1 + 455400\ X_2 + 921300000\ \ X_3 - 2.0412\text{e}11\ \ X_4 + U + \delta(x,t)]) < 0 \quad (16)$$

To satisfy the Lyapunov candidate of stability, input manipulation, Eq. (17), was proposed which was then substituted to Eq. (16).

$$U = \varphi_1 X_1 + \varphi_2 X_2 + \varphi_3 X_3 + \varphi_4 X_4 + \varphi_5 \quad (17)$$

$$\sigma X_1(971 + \varphi_1) + \sigma X_2(455400 + \varphi_2) + \sigma X_3(921300000 + \varphi_3) + \sigma X_4(\varphi_4 - 2.0412\text{e}11) + \sigma(\varphi_5 + \delta(x,t)) < 0$$

To make above equation less than zero, all parts were designed to be negative. Further analyses to make all parts to be negative are presented in following discussions:

- $\sigma X_1(971 + \varphi_1) < 0$
  - If $\sigma X_1 > 0$

    $(971 + \varphi_1) < 0 \quad \rightarrow \quad \varphi_1 < -971$
  - If $\sigma X_1 < 0$

    $(971 + \varphi_1) > 0 \quad \rightarrow \quad \varphi_1 > -971$

  To satisfy this condition, switching function, Eq. (18), was employed.

$$\varphi_1 = -k_1 \operatorname{sgn}(\sigma X_1) \quad (18)$$

  Because k_1 must be greater than 971, k_1 was then set to 975.

- $\sigma X_2(455400 + \varphi_2) < 0$
  - If $\sigma X_2 > 0$

    $(455400 + \varphi_2) < 0 \quad \rightarrow \quad \varphi_2 < -455400$
  - If $\sigma X_2 < 0$

    $(455400 + \varphi_2) > 0 \quad \rightarrow \quad \varphi_2 > -455400$

  To satisfy this condition, switching function, Eq. (19), was employed.

$$\varphi_2 = -k_2 \operatorname{sgn}(\sigma X_2) \quad (19)$$

  Because k_2 must be greater than 455400, k_2 was then set to 455405.

- $\sigma X_3(921300000 + \varphi_3) < 0$
  - If $\sigma X_3 > 0$

    $(921300000 + \varphi_3) < 0 \quad \rightarrow \quad \varphi_3 < -921300000$
  - If $\sigma X_3 < 0$

    $(921300000 + \varphi_3) > 0 \quad \rightarrow \quad \varphi_3 > -921300000$

  To satisfy this condition, switching function, Eq. (20), was employed.

$$\varphi_3 = -k_3 \operatorname{sgn}(\sigma X_3) \quad (20)$$

Because k_3 must be greater than 921300000, k_3 was then set to 921300005.

- $\sigma X_4(\varphi_4 - 2.0412e11) < 0$
  - If $\sigma X_4 > 0$

    $(\varphi_4 - 2.0412e11) < 0 \quad \rightarrow \quad \varphi_4 < 2.0412e11$
  - If $\sigma X_4 < 0$

    $(\varphi_4 - 2.0412e11) > 0 \quad \rightarrow \quad \varphi_4 > 2.0412e11$

To satisfy this condition, switching function, Eq. (21), was employed.

$$\varphi_4 = -k_4 \operatorname{sgn}(\sigma X_4) \quad (21)$$

Because k_4 must be greater than 2.0412e11, k_4 was then set to 204120000005.

- $\sigma(\varphi_5 + \delta(x,t)) < 0$
  - If $\sigma > 0$

    $(\varphi_5 + \delta(x,t)) < 0 \quad \rightarrow \quad \varphi_5 < -\delta(x,t)$
  - If $\sigma < 0$

    $(\varphi_5 + \delta(x,t)) > 0 \quad \rightarrow \quad \varphi_5 > -\delta(x,t)$

To satisfy this condition, switching function, Eq. (22), was employed.

$$\varphi_5 = -k_5 \operatorname{sgn}(\sigma) \quad (22)$$

In this function, $k_5 > |\rho|$, which represents the maximum amplitude of nonlinearities, disturbance, and white noise. In this study, $|\rho|$ was assumed to be 9 (Fig. 7) so k_5=10.

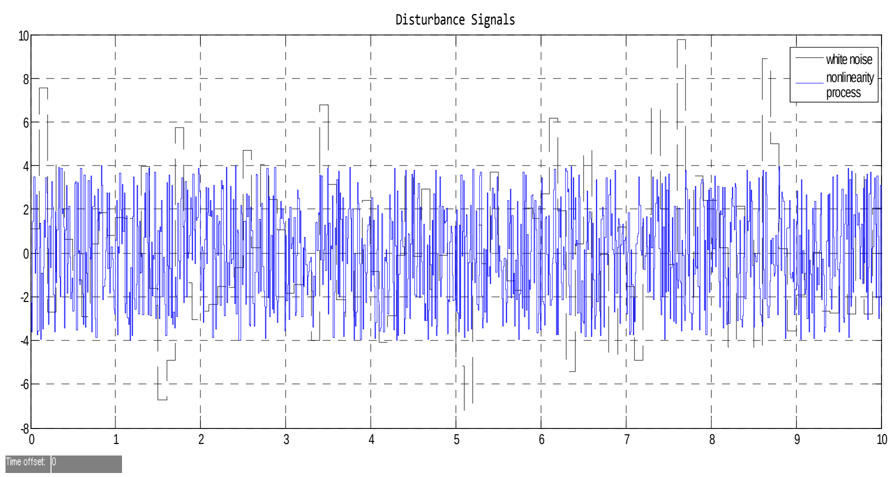


Figure 7. Representation of disturbance signals: nonlinearities and white noise.

After deriving all values satisfying Lyapunov candidate, all equations, from Eq. (18) to (22), were substituted to Eq. (17), yielding:

$$\begin{aligned}U &= \varphi_1 X_1 + \varphi_2 X_2 + \varphi_3 X_3 + \varphi_4 X_4 + \varphi_5 \\ &= -k_1 X_1 \operatorname{sgn}(\sigma X_1) - k_2 X_2 \operatorname{sgn}(\sigma X_2) - k_3 X_3 \operatorname{sgn}(\sigma X_3) \\ &\quad - k_4 X_4 \operatorname{sgn}(\sigma X_4) - k_5 \operatorname{sgn}(\sigma) \\ &= -975 X_1 \operatorname{sgn}(\sigma X_1) - 455405 X_2 \operatorname{sgn}(\sigma X_2) - 921300005 X_3 \operatorname{sgn}(\sigma X_3) \\ &\quad - 204120000005 X_4 \operatorname{sgn}(\sigma X_4) - 10 \operatorname{sgn}(\sigma)\end{aligned}$$

3.2 Fuzzy controller

Fuzzy controller was used to decrease both chattering due to sliding mode process and output error. Inputs of Fuzzy controller were error (e = output – reference) and change of error ($\Delta e = e_t - e_{t-1}$), which were then scaled from -5 to 5 (Fig. 8). To scale both error and change of error, observations found that the values of them were divided by 40 and 4, respectively. In this study, membership functions of inputs and output were divided to be positive big (PB), positive small (PS), zero (Z), negative small (NS), and negative big (NB). Mamdani type, as shown in Fig.9, was then used as rule processing while centroid of area was employed in defuzzification process (Nurhadi, 2010).

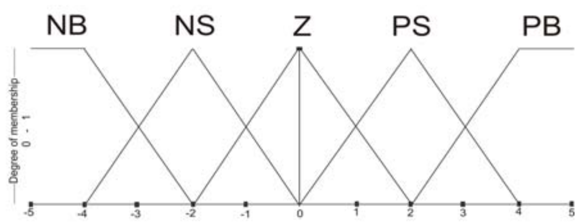


Figure 8. Membership function.

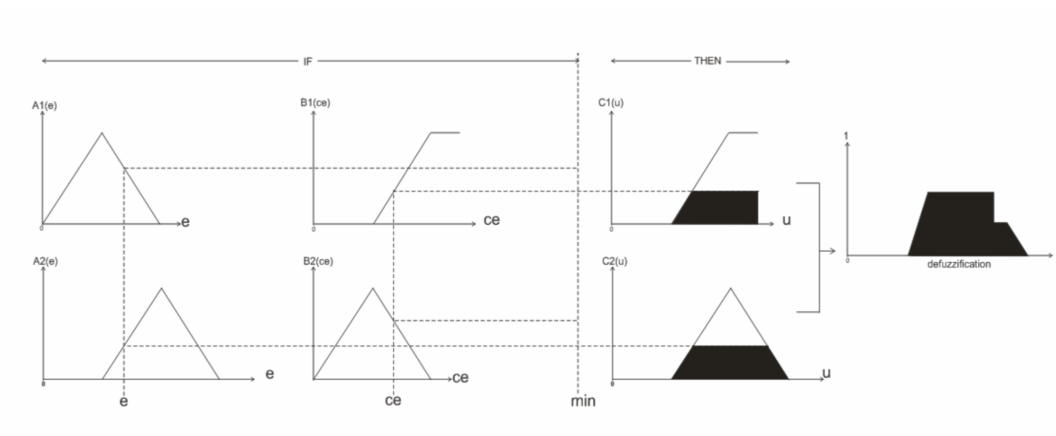


Figure 9. Mamdani's rule processing..

Table 1: Rule evaluation.

CE/E	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

As Fuzzy controller intended to decrease both chattering and output error, the postprocessing of controller output was separated based on its purpose. To decrease output error, Fuzzy controller used input correction, as stated in Eq. (23), which was then added to input manipulation (illustrated in Fig. 5). For another purpose, the output of Fuzzy controller was used as gain in switching process (denoted as K_{fuzzy}). As stated in Eq. (24), the maximum gain is one, which means that sliding mode control uses its original switching. In case of small dynamic in error and change of error, the gain will also be smaller so that chattering can be decreased over the time.

$$\Delta V = \frac{V \ x \ Fuzzy\,controller's\,output}{4} \tag{23}$$

$$K_{fuzzy} = \left| \frac{Output \ fuzzy}{5} \right| \tag{24}$$

4. RESULTS AND DISCUSSION

Control strategy was simulated in MATLAB program with computer specifications: Windows operating system and 2 GB of memory. Sliding mode control was first employed to analyze the output response including chattering phenomena. In this simulation, the signals in Fig. 7 represented disturbances in injection molding process due to physical behavior (such as plastic melt) and environmental condition (such as high temperature and pressure). As shown in Fig. 10, sliding mode control could follow velocity set point, but output deviation and chattering phenomena were very obvious. To overcome these drawbacks, Fuzzy controller was then applied (the controller integration was thus called as Fuzzy Sliding Mode Control (FSMC)). The controller result, as shown in Fig. 11, could follow the velocity set point with small deviation and decrease chattering significantly. Since injection molding process is more than one cycle (Tan and Tang, 2002), two cycles of velocity set point was also used as reference to check the robustness of controller. As shown in Fig. 12, FSMC could still follow the set point even more than one cycle.

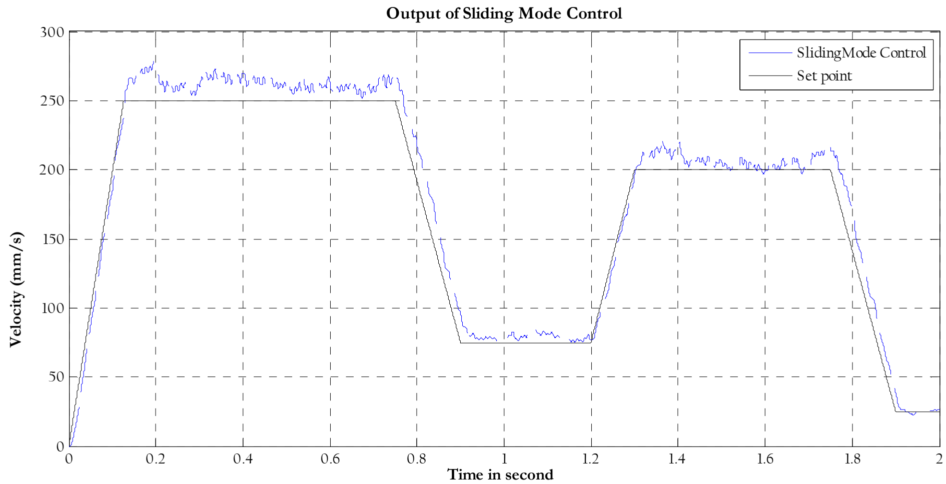


Figure 10. Result of Sliding Mode Control.

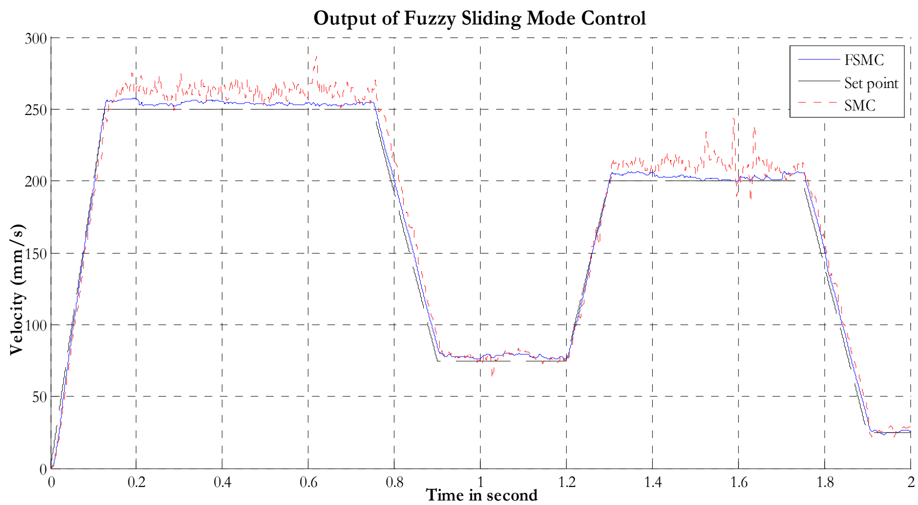


Figure 11. Result of Fuzzy Sliding Mode Control.

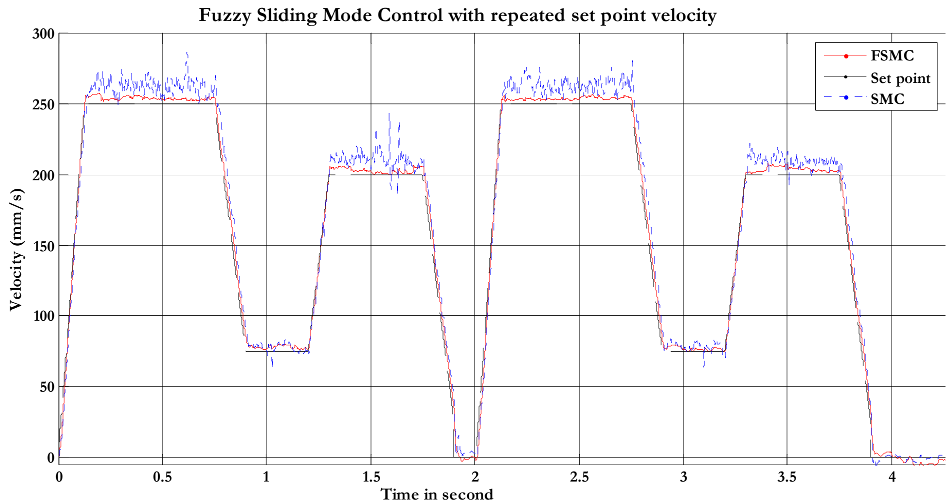


Figure 12. Result of Fuzzy Sliding Mode Control with two cycle of velocity set point.

5. CONCLUSION

In this study, injection velocity during filling phase in injection molding machine was analyzed. Robust and adaptive control (Fuzzy Sliding Mode Control) was proposed to control the velocity in finite time. In this control strategy, sliding mode control intended to overcome system dynamics, while Fuzzy controller decreased both output error and chattering phenomena due to sliding mode process. The results showed that proposed control could decrease chattering phenomena and follow velocity set point with small error. The two cycles of set point were also presented to examine controller's robustness. In future, this proposed control can be potentially applied in real system.

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