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Invited Paper

Switching Control and Strain Suppression Using Ball Screw Drive Devices

Kotaro Minoda[1, a], Shinji Wakui[1, b], Daigo Hotta[2], Hiroshi Morita[2]
[1]Graduate School of Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei-shi, Tokyo 184-8588, Japan
[2]Sumitomo Heavy Industries, 731-1, Naganumahara, Inage-ku, Chiba-City, 263-0001, Japan
[a] <s142677v@st.go.tuat.ac.jp>, [b] <wakui@cc.tuat.ac.jp>,

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Abstract. Ball screw drive devices have been widely used as part of industrial machines. For example, injection molding machines are also one of them. They have been required to increase the speed for mass production. However, high speed causes strains in the machine’s frame. This paper describes switching control and strain suppression. The control method is designed, and the actual machine experiment using ball screw drive device is performed.

1. Introduction

Driving elements with ball screws are one of the electric linear motion mechanisms and are widely used as part of industrial machines. For example, injection molding machines that mold familiar plastics are one of the industrial machines in which the application of ball screws is expanding in recent years. This is due to the advancement of electric motors from hydraulic drive to improve energy saving and controllability [1]. Although high-speed operation is most important continuous task to respond to mass production, its operation brings out some new problems [2]. The injection molding machine has a number of driving units, and the units perform a high speed reciprocating operation. Therefore, large reaction force is generated from the large driving units. As a result, in the practical field, the large reaction force generated from the mold clamping device for molding plastic cause cracks in the base supporting the mold clamping device. Production stops due to repair work of the device, resulting in great loss.

In this paper, a small model of the driving unit of the electric injection molding machine is constructed, and an operation method by switching control and a method of suppressing strain at the time of operation are examined. Firstly, experimental configuration using the small model is explained. Next, the reciprocating operation imitating the actual movement of the mold clamping device is reproduced by the switching control. Then, the small model is placed on the base. The strain is measured and some attempts to suppress the strain are made. Finally, the effectiveness and future prospects of the control methods are described.

2. Experimental Configuration

Motor and ball screw are the common parts of injection molding machines. The small model is created using those parts. Fig. 1 shows the experimental setup. The command signal transmits from the DSP to the servo amplifier and supplies power to the AC servomotor. The ball screw connected to the flexible coupling converts the rotational motion from the motor to the rectilinear motion, thereby the stage operates. The positioning information of the stage is acquired from the encoder of the motor and sent to the DSP. This device operates under PI-D control and the block diagram is shown in Fig. 2. A general positioning waveform is shown in Fig. 3. Each parameter of PID controller is tuned $K_P = 0.6$, $K_D = 2.1$, $T_I = 3.0$ s individually to move 10 mm in about 3 seconds.

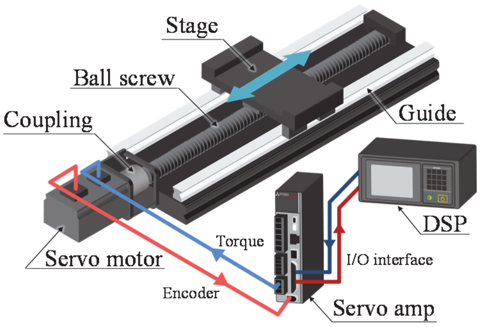


Fig. 1. Experimental setup

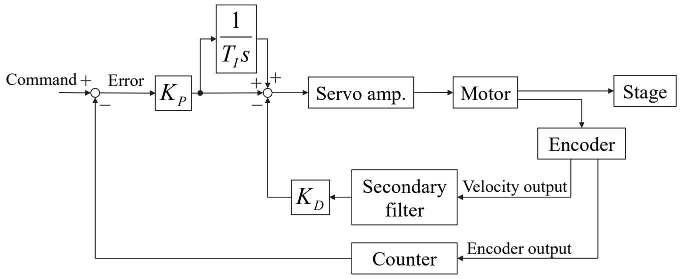


Fig. 2. Block diagram of PI-D control

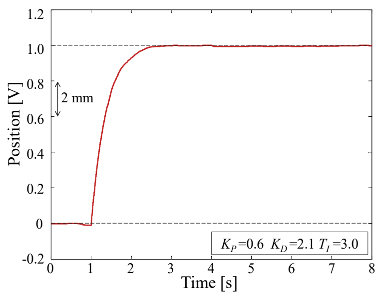


Fig. 3. Positioning of ball screw drive device

3. Switching Control

3.1 Control Design

In order to simulate the reciprocating operation of one cycle of the injection molding machine, new control system is designed. The block diagram is shown in Fig. 4. In addition to the PI-D control shown in Fig.2, this control system is possible to temporarily stop the stage at an arbitrary time, to automatically return the stage to the origin, and also to change the parameters in the going and the returning (hereinafter, this control system is called the "switching control"). By using the Trigger block, the current position of the stage is held by the stop signal and input to command, thereby the stage stops temporarily. Furthermore, by delaying for an arbitrary time period using the Transport delay block, the stage stops on the spot during the time. When the time is over, the second switch inputs the value of the origin to PI-D control and the stage returns to the origin. Each PID gain can also be switched according to the stop signal by the Switch block. Fig. 5 shows the positioning waveforms by actual machines using the switching control. By switching the parameters $K_{P1} = 2.1$, $K_{D1} = 1.5$, $T_{I1} = 3.0$ s to $K_{P2} = 2.4$, $K_{D2} = 0.7$, $T_{I2} = 3.0$ s, the figure indicates the different operations of the stage in the going and the returning. However, the stage could not completely get back to the origin in the returning.

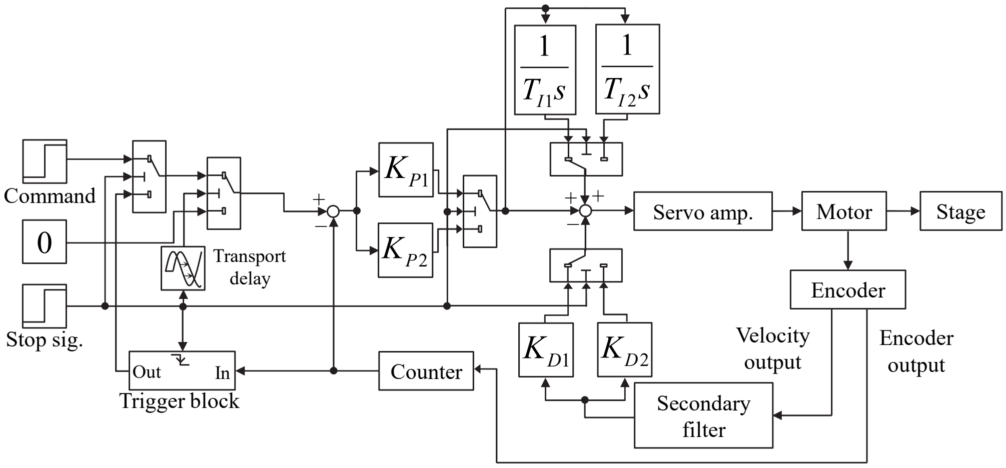


Fig. 4. Switching control

3.2 Applying Reset Integrator

The possible reason why the stage could not completely return to the origin is that the output of the integrator in the going still remains after switching to the integrator in the returning. Therefore, the integrators are redesigned so that the integrator will be reset at the stop signal. The positioning waveform of the stage after the application of the resigned integrators is shown in Fig. 6. The figure shows that the stage returns to the origin more smoothly and quickly compared to the conventional integrator. Then the reset integrator is a key consideration for the switching control.

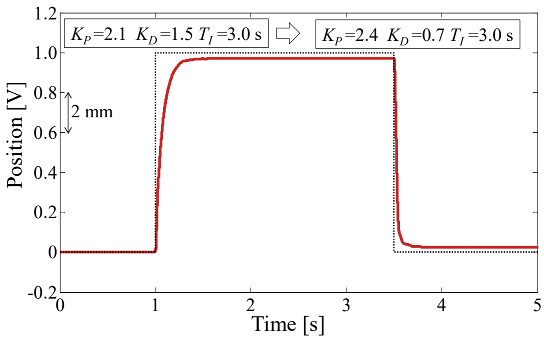


Fig. 5. Positioning by switching control

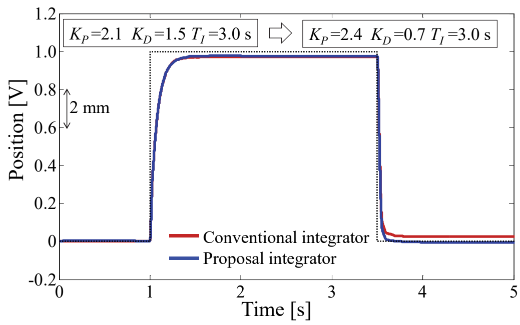


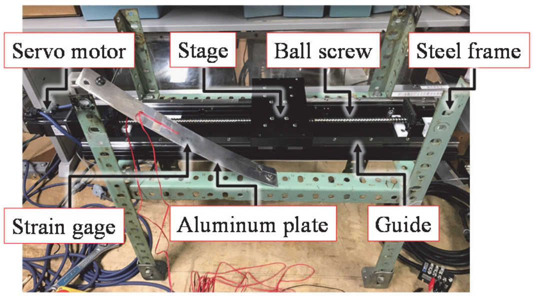
Fig. 6. Speeding up due to reset integrator

4. Measuring and Suppression of Strain

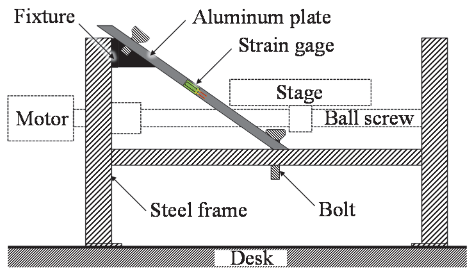
4.1 Measuring of Strain

We attempt to measure the strain by using the small model which can simulate the reciprocating operation. First, the stage is equipped with the handmade frame. Fig. 7(a) shows the frame and the peripheral devices. Fig. 7(b) shows the side view of the schematic representation. The strain measures the bending strain of an aluminum plate with 1 mm in thickness. The aluminum plate is fixed to the frame obliquely with bolts for detecting the larger strain. Two strain gages (KFGS-1-20-C1-23L3M2R) are attached to the aluminum plate, connected to the bridge box (DB-120A), and the output voltage is sent to the DSP by using the strain amplifier (AM50).

The positioning and the strain waveforms are measured at overshooting in order to intentionally apply a large reaction force. Each parameter of PID controller is tuned K_P = 2.4, K_D = 0, T_I = 3.0 s individually. The results are shown in Fig. 8. The strain waveform is generated in the starting up and the stopping of the stage. The reaction force associated with the stage operation is transmitted to the entire frame, whereby vibration of the strain waveform continues in about one second. In addition, the polarity of the strain is output in synchronization with the stage operation. Fig. 9 shows the waveforms of positioning and strain using the parameters of the reciprocating operation. When the stage moves quickly in the returning, the bigger strain is measured than that in the going. Suppression of the strain by control is considered from the next section.



(a) Handmade frame and peripheral device



(b) Schematic representation

Fig. 7. Measuring of strain

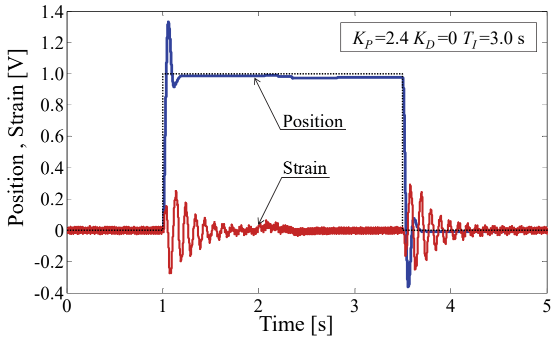


Fig. 8. Positioning and strain waveforms at overshooting

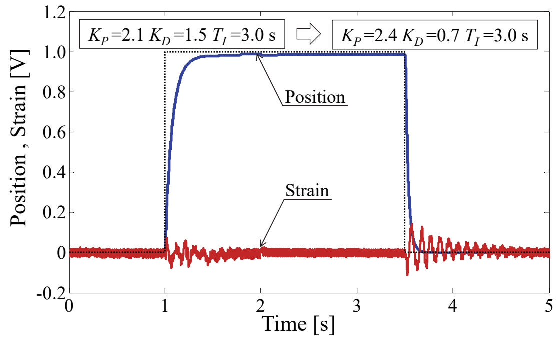


Fig. 9. Positioning and strain waveforms by switching control

4.2 PI-D Control

Let us consider the influence of PI-D control on strains. Figs. 10 and 11 show the positioning and the strain waveforms at start-up when K_D = 0.4, 2.1. Each parameter of PI compensator is set to K_P = 2.4 and T_I = 4.0 s. The results show that strain is suppressed by the effect of damping by increasing K_D. However, delay of the positioning time is an issue.

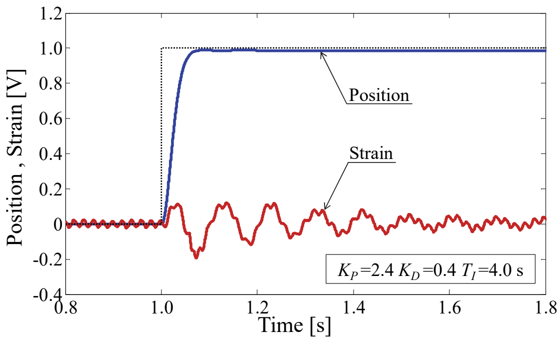


Fig. 10. Positioning and strain waveforms at start-up

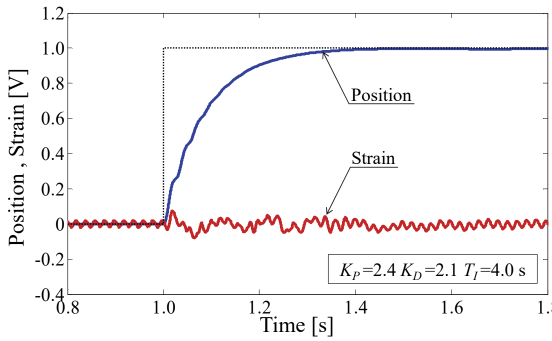
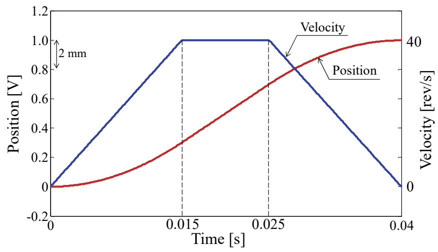


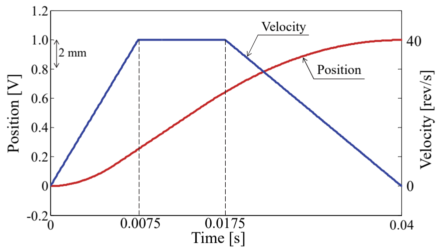
Fig. 11. Strain suppression by damping

4.3 Positioning Profile

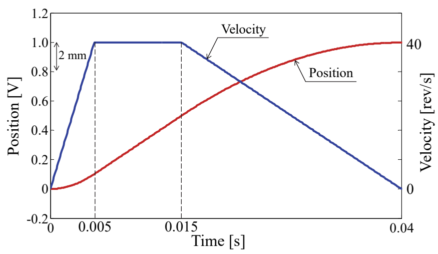
In PI-D control, the suppression of strain is confirmed, however, it is difficult to suppress the strain while keeping the high-speed operation. Therefore, in order to suppress the strain while maintaining the high-speed operation, experiments are performed using positioning profiles [3]. These positioning profiles can change the acceleration and the deceleration times. Fig.12 shows the trapezoidal acceleration and deceleration of each profile. The maximum velocity of all profiles is set to 40 rev/s. Profile 1 is constant at 0.015 s for both acceleration and deceleration times, and profiles 2 and 3 are shortened to 0.0075 s and 0.005 s for acceleration time, respectively. Since the trapezoidal acceleration and deceleration are velocities, measurement is performed by inputting the integrated waveform as shown in Fig. 12 to the control system as a positioning profile. The measurement results are shown in Fig. 13. Each parameter is set to K_P = 2.4, K_D = 0.4, T_I = 4.0 s. However, no significant change in the strain waveform was observed by changing the profile. The reason for no change is that the influence of acceleration and deceleration in moving of the stage is insignificant, and the strain due to the reaction force generated at the time of acceleration and stopping is more influential. Furthermore, since the persistent vibrations are occurring even after the positioning is completed, it is necessary to newly apply the force to the stage by another method to suppress the strain.



(a) Profile 1

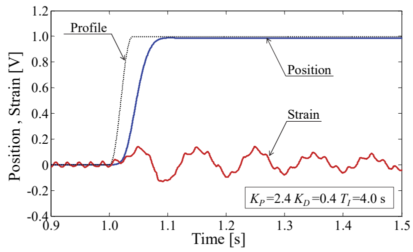


(b) Profile 2

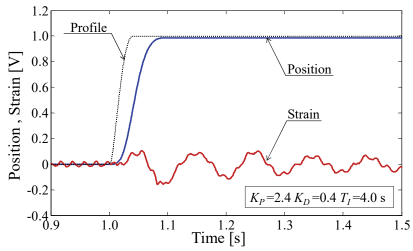


(c) Profile 3

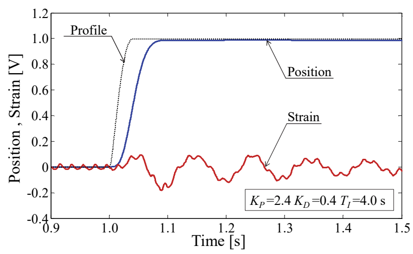
Fig. 12. Positioning profiles



(a) In the case of profile 1



(b) In the case of profile 2

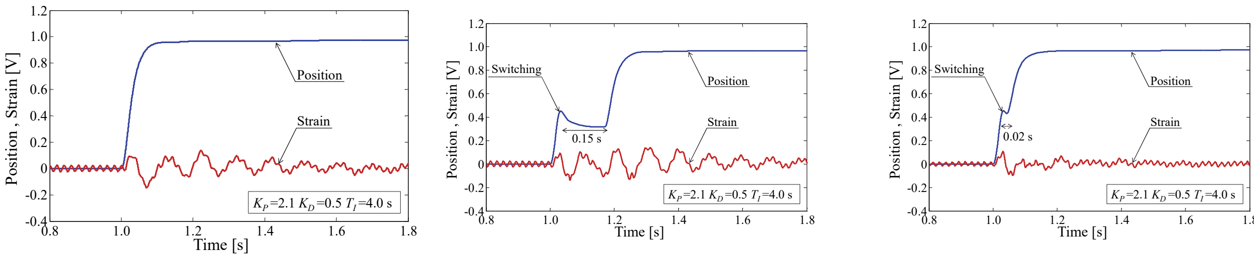


(c) In the case of profile 3

Fig. 13. Positioning and strain waveforms

4.4 Bang-Bang Control

As shown in Section 4.3, the strain is generated at the time of starting and stopping, and acceleration occurs as the stage speeds up. Then suppression of the strain cannot be expected if the control system only uses the positioning profile. Therefore, Bang-Bang control [4] is applied. Command values are set from 0 to 1 in step signal input and profile operation so far. In contrast, in Bang-Bang control, the switching control is performed during positioning and the stage is controlled stepwise. In Bang-Bang control, the stage pauses temporarily and reaccelerates in the middle of positioning, then new strain is generated. The final strains are suppressed when the strain occurring at the initial acceleration and the new strain occurring during positioning are superposed well. Fig. 4 shows that the block diagram is the same as the switching control. 0 is input as the command value after switching, whereas 1 is input in this Bang-Bang control. Measurement is carried out with switching timing set at 1.02 s, stop time set to 0.15 seconds and 0.02 seconds. Experimental results are shown in Fig. 14. As shown in Fig. 14(b), when the stop time is 0.15 seconds, the strain of the same phase is superposed, then the strain could not be suppressed. However, as shown in Fig. 14(c), with the stop time of 0.02 seconds, the strain of the reverse phase is superposed, and therefore the strain could be suppressed. In the PI-D control, time delay of positioning is an issue, however, it was possible to suppress the strain while operating at high speed. The switching timing will be a future task.



(a) Only PI-D
(b) Bang-Bang control (0.15 seconds stop)
(c) Bang-Bang control (0.02 seconds stop)

Fig. 14. Positioning and strain waveforms

5. Conclusion

Switching control using the ball screw drive devices was attempted to simulate the reciprocating operation of injection molding machines to suppress strains. The reciprocating motion and the necessity of the reset integrator were confirmed by actual machine experiments. Furthermore, the experimental environment for strain measurement was prepared, and the detection of strain by positioning operation was confirmed. We attempted to suppress strains by PI-D control, profile operation, and Bang-Bang control. In Bang-Bang control, strains could be suppressed while maintaining the high-speed operation. As a future task, the mathematical switching timing of Bang-Bang control, and control method which is more effective will be needed to consider.

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