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Inertia Force Problem and Nozzle Contact Mechanism of Linear Motor Drive Injection Molding Machine

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ABSTRACT

This paper presents the inertial force problem of ultrahigh-speed injection molding machine using linear motors, and presents its solutions. To make very thin products by injection molding, very high injection speed is required, and linear motors are used for this purpose. However, direct drive by linear motors may cause brief nozzle separation from the sprue bushing because of the inertia force which is as large as the total output thrust of the linear motors, and this momentary separation can cause molten plastic to leak. In this paper, two solutions are proposed for this inertia force problem. One is the mechanical cancellation of the inertia force, and the other is to increase the nozzle contact force. With the latter solution, the stationary platen bending worsens, so a new nozzle contact mechanism is also proposed, which can prevent the stationary platen bending.

Key Words : Inertia force, Linear motor, Injection molding, Nozzle contact, High speed injection

1. Introduction

With the on-going development of electronic equipment, the demand for ultra-thin-walled products is increasing. Cellular phone cases, battery packs, speaker cones and IC memory cards are some examples of such products. As a production method of such ultra-thin-walled products, injection molding has merits of high productivity, net-shape manufacturing, low production cost, etc. However, as the theoretical cooling time of an injected plate is proportional to the square of wall thickness, injection speed needs to be very high to produce ultra-thin products without short shot.[1]

Generally, "ultrahigh-speed injection" is the term used for injection speeds (the speed of injection screw or plunger) over 800 or 1000mm/s. This ultrahigh-speed injection has only been possible by special hydraulic injection machines equipped with a big accumulator with their maximum injection speed in the range of 800-1500 mm/s.

Because of the need for energy efficiency and controllability, there had been a strong requirement for ultrahigh-speed all-electric injection molding machines. However, injection speeds over 600mm/s were difficult to produce using a rotational servomotor and a ballscrew. Because the maximum rotational speed of high-power industrial servomotors is below 4000rpm, the production of ultrahigh-speed linear motion requires a ballscrew pitch that is impractically large. Other mechanisms that converts rotational to linear motion, such as pinion-rack and RV rack, have been considered, but they are not suitable substitutes for the ballscrew mechanism either because the conversion ratio (displacement/rotation angle) of the mechanism is too high or the load capacity is not high enough. Moreover, in the case of rotational servomotors, the rotor inertia itself is very large compared to the inertia of the linearly moving part; therefore, high acceleration is impossible to achieve.

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To overcome the performance limit from using rotational servomotors, an ultrahigh-speed injection molding machine that uses linear motors has been developed recently.[2] This paper briefly reports the developed linear-motor-drive injection molding machine, and presents the inertial force problem generated from using linear motors, and its solutions.

2. Linear Motor Drive Injection Molding Machine

The linear motor drive injection molding machine has basically the same construction of ballscrew type injection molding machines and is composed of injection unit, clamping unit, control unit and frames (Fig. 1). Among these, injection unit is a completely different structure from that of a ballscrew type injection molding machine, while other units have almost the same structure and just need a reinforced structure to endure the higher pressure and load.

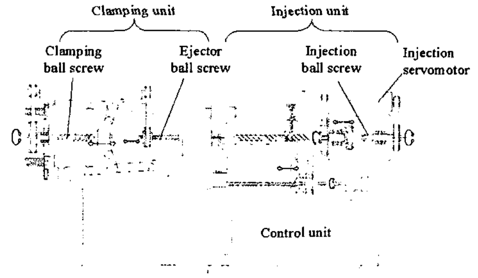


Fig. 1 Typical construction of all-electric injection molding machine

Fig. 2 shows the structure of an injection unit. Four linear motors were used to increase the injection force, and these linear motors were installed in a rectangular orientation to cancel the attractive force applied to the moving part.

A loadcell was installed in front of the moving part to indirectly measure the injection pressure. Four linear motors were synchronously controlled by using position feedback signal from an absolute type linear encoder (Fig. 3). The maximum injection speed is 2000 mm/s, which is higher than that of a hydraulic ultrahigh-speed injection molding machine. Fig. 4 is the experimental results showing the acceleration performance of the injection unit. The injection speed reaches 2000 mm/s in 16 ms, and decreases to zero in 12 ms. The acceleration rate is more than 20 times that of conventional ballscrew type injection molding machines. Figs. 5 and 6 show the card shells for smart media, in which the mid-section is 0.15mm in thickness. In case of using PC+ABS material, the injection speed of 600mm/s was needed to eliminate the burr, burning and short shot. In the case of PC material the injection speed of 2000mm/s was needed for the production of non-defective products.

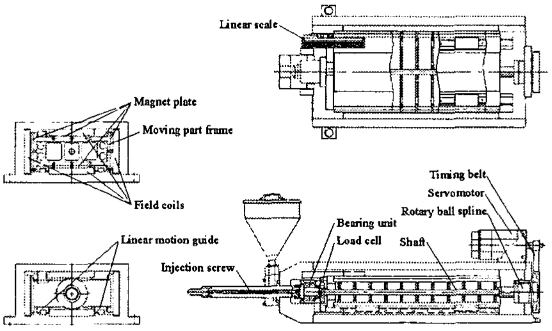


Fig. 2 Structure of ultra-high-speed injection molding machine

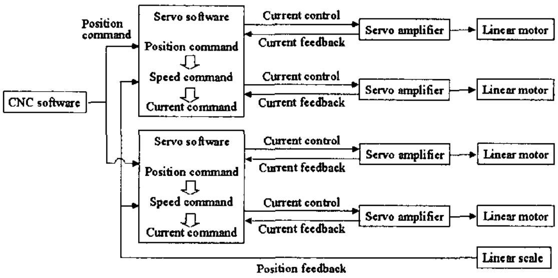


Fig. 3 Control system for four linear motors

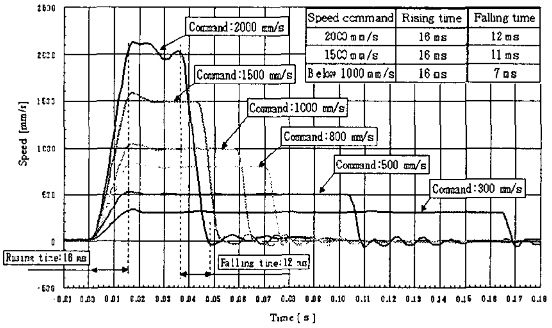
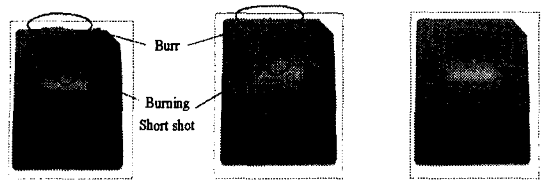
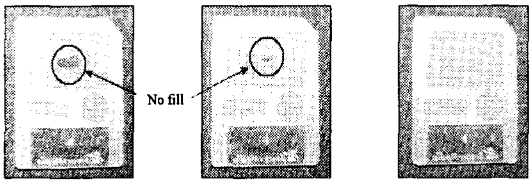


Fig. 4 Acceleration performance of ultra-high-speed injection molding machine



(a) Injection speed: 300mm/s (b) Injection speed: 500mm/s (c) Injection speed: 600mm/s

Fig. 5 Examples of molded card shell (smart media) (Material: PC+ABS, Thickness of thin part: 0.15mm)



(a) Injection speed: 1500mm/s (b) Injection speed: 1800mm/s (c) Injection speed: 2000mm/s

Fig. 6 Examples of molded card shell (smart media) (Material: PC, Size: 45mm´37mm, Thickness of thin part: 0.15mm)

3. Ballscrew Mechanism vs Linear Motor Mechanism

3.1 Comparison of acceleration performance

From Fig. 1, in case of ballscrew type injection units, a rotational servomotor rotates a ballscrew through a timing belt and pulleys, and the ballscrew moves an injection screw linearly. Table 1 compares the acceleration performances of a ballscrew type injection unit and a linear motor type injection unit. In Table 1, the maximum acceleration rates are calculated from the motor torque and rotational inertia or from the motor thrust and mass. In the case of the ballscrew type injection unit, the maximum injection force is more than four times that of the linear motor type (278000 N vs. 62000 N), and the moving part is lighter than the linear motor type (210 kg vs. 310 kg). However, the maximum acceleration rate does not even reach 5 % that of the linear motor type. This is because, in case of the ballscrew type injection mechanism, rotational inertia is large and it becomes enormous when it is converted into a linearly moving mass with reduction (reduction has square effects). This result shows that the ballscrew types are essentially inferior to the linear motor types in acceleration performance.

3.2 Comparison of inertia force

In the case of ballscrew type injection mechanisms mentioned above, most of the inertia force is the inertia moment which tries to rotate the injection unit (solid arrow in Fig. 7), and this moment does not affect the linear motion in the injection direction. Ballscrew type injection mechanisms also generate inertia force in the injection direction (dotted arrow in Fig. 7), but the magnitude is not large due to the low acceleration rate. For example, in the case of the ballscrew type injection mechanism of Table 1, the maximum inertia force in the injection direction is about 1400 N, as calculated from the moving part mass of 210 kg and the maximum acceleration of 6.6 m/s. Generally, nozzle contact force has a margin of over several thousands of N, and therefore this amount of inertia force does not cause nozzle break (nozzle break means that the nozzle momentarily loses contact with the sprue bushing resulting in leakage of the molten resin). However, in the case of linear motor type injection molding machines, the inertia force is directly applied to the mainframe of the injection unit in the injection direction. Fig. 8 shows the forces applied to the injection unit during the injection process (friction forces are neglected in Fig. 8).

Table 1 Comparison of inertia and maximum acceleration of injection mechanism: Ball screw type vs linear motor type

Ball screw type	Maximum motor torque	264 N·m
	Servomotor rotor inertia	0.0117 kg·m^2
	Driving pulley inertia	0.00393 kg·m^2
	Slave pulley & ballscrew inertia	0.159 kg·m^2
	Reduction ratio of pulleys	38/102
	Ballscrew pitch	16 mm
	Maximum injection force	278000 N
	Moving part mass	210 kg
	Equivalent moving part inertia	**0.000189 kg·m^2**
	Total equivalent inertia	**0.0379 kg·m^2**
	Maximum acceleration	**6.61 m/s^2**
Linear motor type	Maximum motor thrust	62000 N
	Moving part mass	310 kg
	Maximum acceleration	**200 m/s^2**

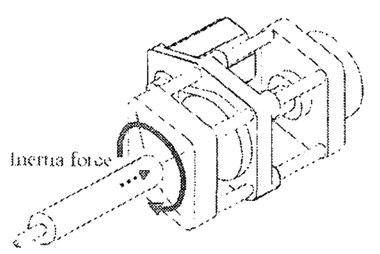


Fig. 7 Inertia forces of ball-screw-type injection unit

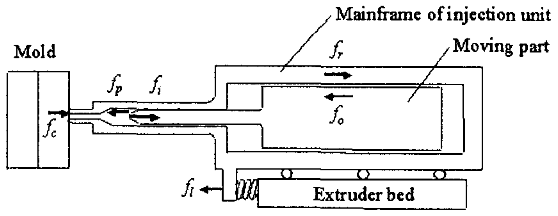


Fig. 8 Forces applied to the injection unit during injection operation

Moving part: $f_o - f_i = m_m a_m$ (1)

Mainframe: $f_p + f_l - f_r - f_c = m_f a_f$

where

f_o = output thrust of linear motors

f_r = reaction force

f_i = injection force

f_p = pressure force

f_c = nozzle contact force

f_l = preload by spring

m_m = mass of moving part

m_f = mass of mainframe

a_m = acceleration of moving part

a_f = acceleration of mainframe

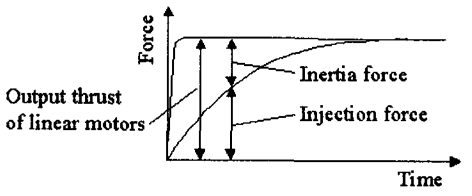


Fig. 9 Inertia force vs. injection force

Due to the compressibility of the molten resin, the initial value of pressure force(f_p) is considered to be zero when the injection screw starts to move (Fig. 9). Because the reaction force(f_r) is equal to output thrust of linear motors(f_0), if preload f_l is smaller than f_0, nozzle break occurs ($f_c = 0$) resulting in the leakage of molten resin.

4. Countermeasures Against the Inertia Force Problem

4.1 Mechanical cancellation of inertia force

As mentioned in section 3, the injection unit moves momentarily by inertia force, and the cause of this movement can be considered as the change of injection unit's center of mass. Therefore, it is possible to cancel the effect of inertia force by fixing the injection unit's center of mass in spite of the movement of the moving part. Fig. 10 through Fig. 12 show injection mechanisms designed to cancel the effect of inertia force.[3] From the figures, it can be seen that there are at least two moving parts; one moves with the injection screw and the other moves in the opposite direction. Also, the two moving parts are connected by link mechanisms whose link factor is the inverse of the moving parts' mass ratio. In these mechanisms, the injection unit's center of mass remains stationary while the moving parts move. In case of the structure shown in Fig. 10 and Fig. 11, the inertia force generates a moment which tries to rotate the injection unit. However, this moment is cancelled by both up and downward forces supporting the injection unit resulting in no overall effect in the injection direction. Fig. 13 explains the link mechanism used in the injection units of Fig. 10 through Fig. 12. From Eq.(2), the upper and lower moving part of this link mechanism

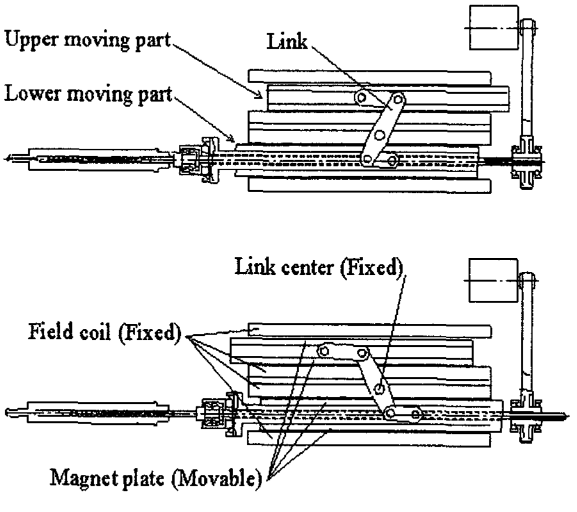


Fig. 10 Inertia-force-canceling mechanism 1

show linear relationship in their displacements.

In case of high-speed milling machines, high-speed laser cutting machines and punching machines that use linear motors, the mainframe is usually fixed to the floor by stud bolts to prevent the machine from shifting due to the inertia force. The above inertia-force-cancellation mechanism can be used when the mass of the moving part does not change much or the speed ratio of the moving parts can be adjusted mechanically.

$$
\begin{aligned}
x_1 &= l\sin\theta + \sqrt{r^2-(l\cos\theta-h)^2} - \sqrt{r^2-(l-h)^2} \qquad (2)\\
x_2 &= kl\sin\theta + \sqrt{k^2r^2-(kl\cos\theta-kh)^2} - \sqrt{kr^2-(kl-kh)^2}\\
&= k\left\{l\sin\theta + \sqrt{r^2-(l\cos\theta-h)^2} - \sqrt{r^2-(l-h)^2}\right\}\\
&= kx_1
\end{aligned}
$$

where x_1 = displacement of upper moving part

x_2 = displacement of lower moving part

k = velocity ratio

l, r, k, h : link parameter

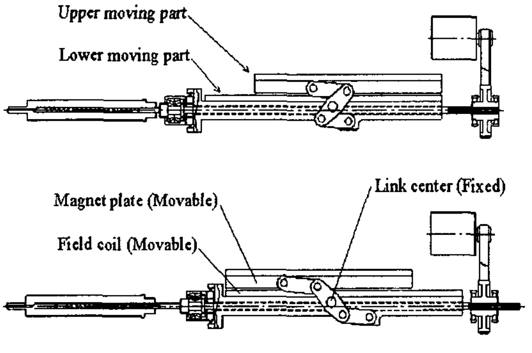


Fig. 11 Inertia-force-canceling mechanism 2

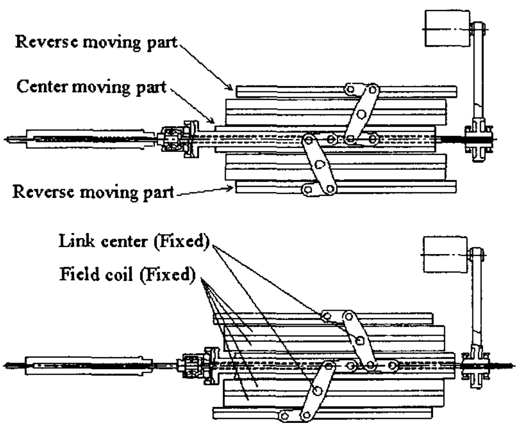


Fig. 12 Inertia-force-canceling mechanism 3

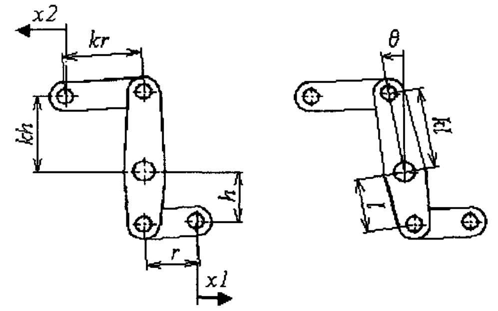


Fig. 13 Link mechanism linearly-connecting the upper and the lower moving part

4.2 Increase of nozzle contact force and new nozzle contact mechanism

The method mentioned in 4.1 is an essential solution for the inertia force problem, but the mechanisms are complex. A simpler solution for the inertia force problem is to increase the nozzle contact force(f_c) more than the linear motor output(f_0). This can be done by merely increasing the capacity of the nozzle contact mechanism that is composed of spring, geared motor and ball screw. However, this leads to another problem. As shown in Fig 14, the nozzle contact force makes the stationary platen bend. The bending increases as the contact force increases. This stationary platen bending caused by the nozzle contact force is a chronic problem in injection molding machines, and for thin-walled molding or precision molding such as a compact disk molding, it becomes even a larger problem. To prevent the stationary platen bending, the nozzle contact mechanism shown in Fig. 15 was previously produced.[4] However with this machine design, two shafts cause an interference with the workspace and in case of swiveling the injection unit, the shafts must be disassembled from the stationary platen.

For these reasons, we designed a new nozzle contact mechanism shown in Fig. 16, which prevented the stationary platen bending and did not cause inconveniences when operating the machine.[5] As it is apparent in Fig. 16, this mechanism cancels the bending moment caused by the height difference between the nozzle contact force and the tensile force of the ball screw by using a connecting block. That is, the bending moment is canceled on the connecting block by a moment generated from the vertical direction forces. The connecting block should be supported freely in the injection direction to allow elastic deformation of the connecting block, but should be restrained in other directions. To support the connecting block as mentioned above, linear motion guides may be used. However, displacement of the connecting block is less than 1mm and flaking may occur at the linear motion guides because of the short stroke.[6] The structure shown in Fig. 16 supports the connecting block using plate springs and can provide the previously mentioned restraints without sliding or rolling surfaces. Notches on the top and bottom of the plate spring considerably reduce the bending stiffness without causing buckling. Fig. 17 shows the experimental results of stationary platen bending by nozzle contact force. Fig. 17(a) represents the conventional nozzle contact mechanism, and Fig. 17(b) represents the new nozzle contact mechanism. It is understood that the bending decreased by more than 99%.

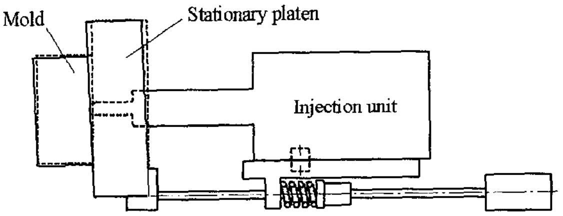


Fig. 14 Stationary platen bending caused by nozzle contact force

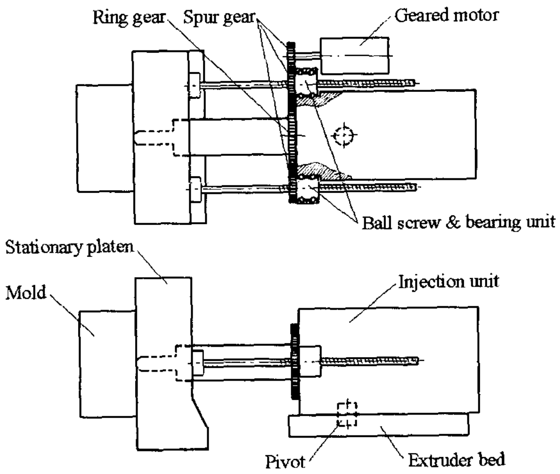


Fig. 15 Existing nozzle contact mechanism preventing stationary platen bending

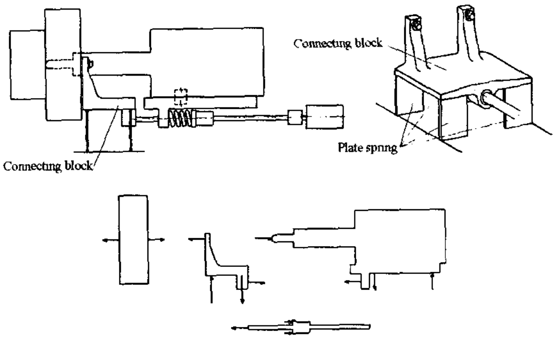
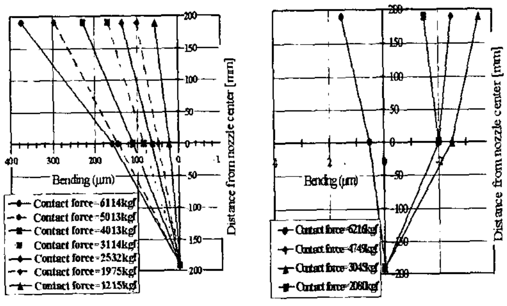


Fig. 16 Nozzle contact mechanism preventing stationary platen bending



(a) Conventional nozzle contact mechanism (b) Newly developed nozzle contact mechanism

Fig. 17 Stationary platen bending by nozzle contact force

5. Conclusions

1) The injection molding machine equipped with linear motors in the injection unit could perform ultrahigh-speed injections of 2000 mm/s.

2) It is difficult for ballscrew type injection molding machines to attain high acceleration performance due to large rotational inertia. The linear motor type injection molding machine has acceleration performance of more than 20 times that of ballscrew type injection molding machines.

3) Linear motors in injection units may cause an inertia force problem. The inertia force may cause nozzle break, resulting in molten resin leakage.

4) To prevent the nozzle break caused by the inertia force, inertia-force-cancellation mechanism can be used. In this mechanism, the center of mass remains stationary while the moving parts move.

5) Nozzle break can also be prevented by increasing the nozzle contact force, but this causes a problem of

stationary platen bending. A new nozzle contact mechanism can prevent the stationary platen bending. This mechanism has a connecting block that cancels the bending moment by using the vertical supporting forces.

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