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반발력 보상 기구 적용 선형 모터 이송 장치의 입력 성형 기법

Input-Shaping Methods for a Linear Motor Motion Stage with a Passive RFC(Reaction Force Compensation) Mechanism

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The residual vibration during the high acceleration and deceleration of a motion stage degrades the manufacturing-system productivity and lifespan. Although a passive RFC mechanism with a movable magnet track reduces the residual vibration of the system base, a magnet track resonance may occur according to the motion profile, and the mover in-position error increases due to the residual vibration of the magnet track. We investigated input-shaping methods for a linear motor motion stage with a passive RFC mechanism. An air-bearing linear motor motion stage with the passive RFC mechanism is built, and the dynamic characteristic of the passive RFC mechanism is identified using a free-vibration test. Then, mover velocity profiles are generated using various input-shaping methods. Further, the effects of the input-shaping methods on the air-bearing linear motor motion stage are investigated by comparing the magnet track oscillation, settling time, and mover in-position error. Finally, several input-shaping methods are applied to reduce the mover rise-time delay for the proposed linear motor motion stage. A properly shaped input motion profile removes the residual vibration of the passive RFC mechanism without any additional devices, as well as reducing the transmitted reaction force and the in-position error.

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NOMENCLATURE

F_t = Thrust force of mover
F_{tran} = Transmitted force
m_{MT} = Mover mass
x_{MT} = Displacement of magnet track
k_{MT} = Stiffness of spring
c_{MT} = Damping of magnet track
$\dot{x}_{MT}$ = Velocity of magnet track
$\ddot{x}_{MT}$ = Acceleration of magnet track

1. Introduction

Moving mass and working area increases associated with enlarged size such as display panel and semiconductor industries require fast response and high precision of a motion stage. In particular, semi-conductor lithography systems require both extreme precision and high speed in very long stroke such as 1 nanometer accuracy and 230 wafers/hour over 2 m stroke.[1,2]

Residual vibration of the system base due to high speed motion has a negative effect on production quality, manufacturing process time and life of the manufacturing equipment. Rapid acceleration or deceleration motion of a stage induces large reaction force and causes the system base to oscillate either with unacceptable amplitude or in long settling time.[3]

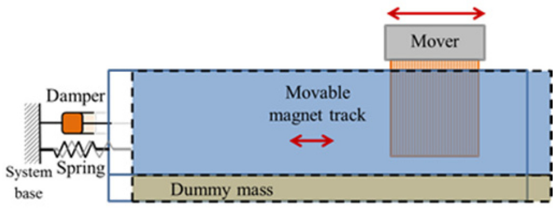
Base vibration of a linear motor motion stage has been reduced with a passive reaction force compensation (RFC) mechanism.[4,5] Although the passive RFC mechanism is compact and cost-effective without any additional external structures or actuator, the passive RFC does not allow in-situ modification of the dynamic characteristic and may have resonance when a motion profile excites natural frequency of the RFC mechanism.[4] An active RFC mechanism using an additional coil can tune its stiffness of the magnet track, and minimize the transmitted force under motion profile variations.[6] However, the active RFC mechanism results in increasing energy and cost requirements due to extra servo amplifier and motion controller.[7] In addition, an eddy-current damper is used to dissipate the residual vibration of the magnet track as an alternative way.[8,9]

Input-shaping method is widely used to reduce mechanical vibration of a motion control system since it generates a command that cancels its own vibration and does not need an additional sensor for feedback control.[10,11] Since the input-shaping method is implemented by convolving a sequence of impulse so that rise time of the motion is delayed proportional to the natural frequency of the vibration. Input-shaping method may resolve residual vibration of the passive RFC mechanism without any additional devices.

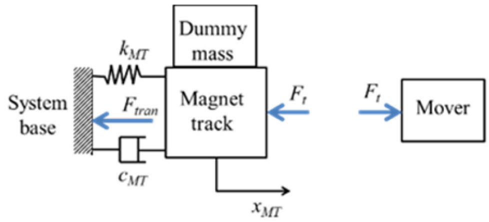
This paper presents input-shaping methods for a linear motor motion stage with a passive RFC mechanism. First, an air-bearing linear motor motion stage with the passive RFC mechanism is built for experimental verification and dynamic characteristic of the passive RFC mechanism is identified with free vibration test. Then, velocity profiles of the mover are generated with various input-shaping methods. In addition, we investigate effects of input-shaping methods on the linear motor motion stage with the passive RFC mechanism by comparing the magnet track oscillation, settling time and in-position error of the mover. Finally, special input-shaping methods to reduce the rise time delay of the mover are investigated for the linear motor motion stage with the passive RFC.

2. Passive RFC Mechanism for a Linear Motor Motion Stage

Fig. 1 shows the schematics of the passive RFC mechanism. When the mover moves due to thrust force (F_t), its reaction force makes the magnet track with dummy mass (m_{MT}) oscillate and create displacement (x_{MT}) since the magnet track is



(a) Schematics of the passive RFC mechanism



(b) Schematic model of the passive RFC mechanism

Fig. 1 The passive RFC for a linear motion stage

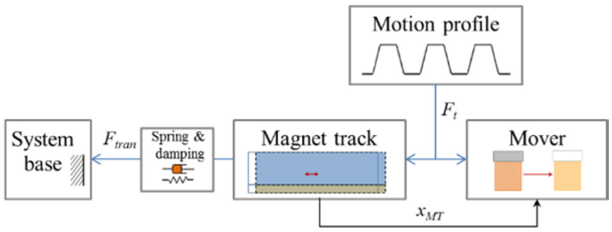


Fig. 2 Mover jitter increase due to magnet track oscillation

supported by spring (k_{MT}) and damper (c_{MT}).[4,5] The equation of motion of the passive RFC mechanism is given by Eq. (1).

$$m_{MT}\ddot{x}_{MT}+c_{MT}\dot{x}_{MT}+k_{MT}x_{MT}=F_t \tag{1}$$

The transmitted force to the system base through spring and damping is expressed with Eq. (2). The reaction force (F_t) is divided into the inertial force of the magnet track and the force of the spring and the damper transmitted to the system base. The magnet track displacement and the transmitted force can be adjusted by changing the dummy mass and the spring stiffness.

$$F_{tran}=c_{MT}\dot{x}_{MT}+k_{MT}x_{MT} \tag{2}$$

The passive RFC mechanism may have residual oscillation of the magnet track after a mover motion so that mover jitter may increase, as shown in Fig. 2. Although the magnet track oscillation reduces transmitted force to the system base ($F_t \rightarrow F_{tran}$), the motion jitter after motion may become large when the motion profile excites natural frequency of the magnet track.

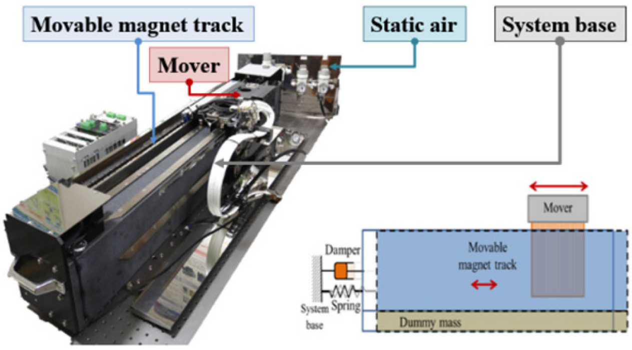


Fig. 3 An air-bearing linear motor motion stage with the passive RFC

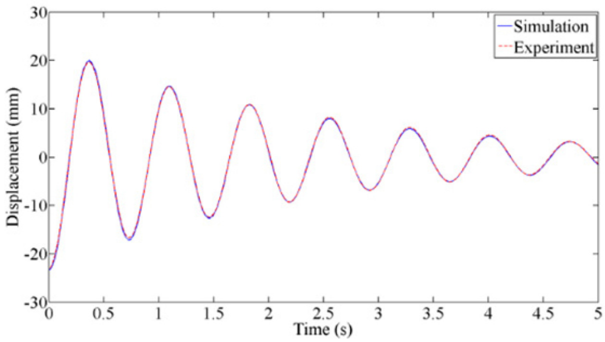


Fig. 4 System identification of modal parameters of the passive RFC mechanism

Table 1 Specifications of an air-bearing linear motor motion stage

Items	Unit	Value
Stroke	mm	580
Force (Continuous/Peak)	N	208/832
Resolution	μm	1
Max. speed	m/s	5
Max. acc	m/s^2	50

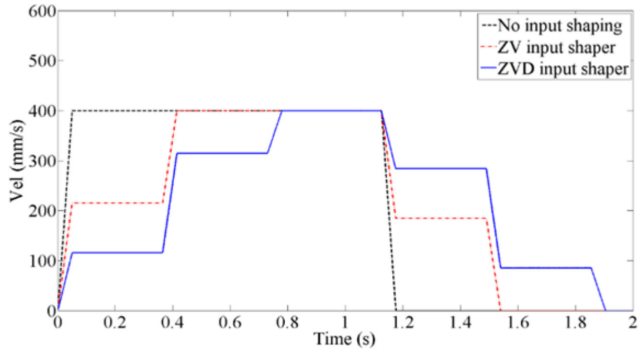
Table 2 Model parameters of the passive RFC mechanism

Parameters	Unit	Value
Mass of magnet track	kg	51.67
Stiffness	N/m	3820
Damping	Ns/m	45
Damped natural frequency	Hz	1.37

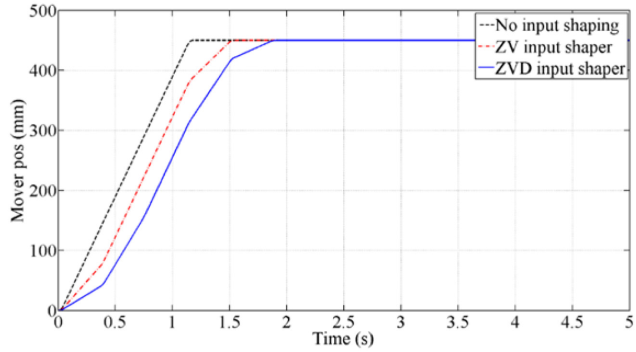
3. Air-Bearing Linear Motion Stage with the Passive RFC Mechanism

3.1 Constitution and Specifications

An air-bearing linear motor motion stage with the passive RFC mechanism is built, as shown in Fig. 3. The specifications of the stage are summarized in Table 1. The stage has in-position error within $\pm 0.4\ \mu m$, straightness with $4.3\ \mu m$ and flatness within $1.7\ \mu m$.



(a) Velocities of original and shaped input motion profiles



(b) Positions of original and shaped input motion profiles

Fig. 5 Original and shaped input motion profiles

3.2 System Identification of the Passive RFC Mechanism

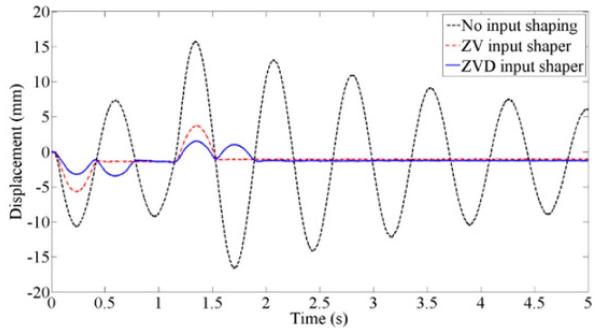
Since dynamic characteristic of the passive RFC mechanism is necessary to apply an input-shaping method, modal parameters of the passive RFC mechanism are identified with free vibration test of Fig. 4 and summarized in Table 2.

4. Input-Shaping Method for the Air-Bearing Linear Motor Motion Stage with the Passive RFC

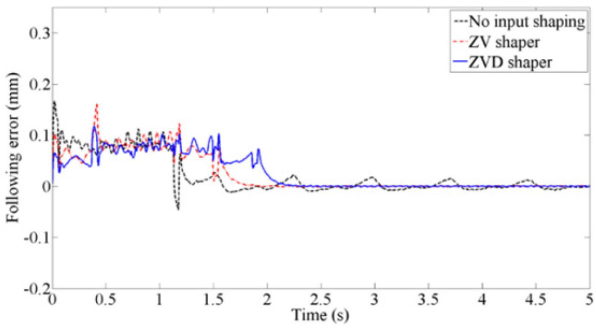
4.1 ZV and ZVD Methods

Input motion profiles with ZV (zero-velocity) and ZVD (zero-velocity derivative) methods[10] are compared with the original motion profile and shown in Fig. 5. The original motion profile has max. 400 mm/s velocity and 450 mm stroke to intentionally excite large residual vibration of the magnet track (or to excite the resonance of the passive RFC).[4]

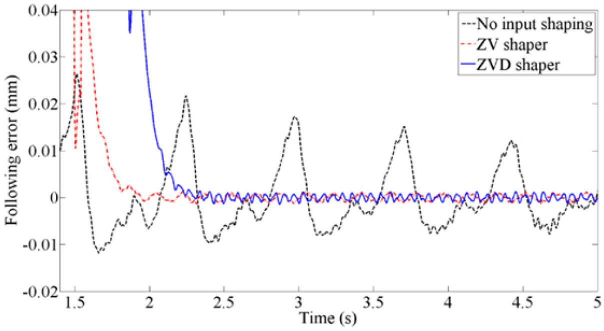
Magnet oscillation and the mover in-position errors for three motions profiles are shown in Fig. 6. As shown in Fig. 6(a), magnet track oscillations for the shaped inputs disappear after



(a) Magnet track oscillations



(b) Mover in-position errors



(c) Mover in-position errors: detailed view

Fig. 6 Magnet trach oscillations and mover in-position errors for original and shaped input motion profiles

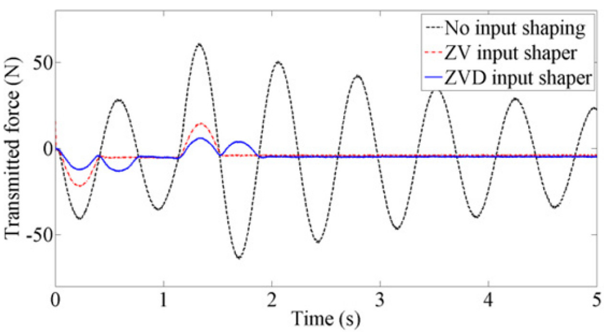


Fig. 7 Transmitted force: original and shaped input motion profiles

motion while the original motion profile generates large residual oscillation of the magnet track. In addition, mover in-position errors can be reduced significantly with the shaped motion profiles,

Table 3 Comparisons of ZV and ZVD methods during and after motion

		ZV	ZVD
During motion	Magnet track oscillation	46.3%	67.1%
	In-position error	3.78%	29.39%
After motion	Magnet track oscillation	89.9%	91.4%
	In-position error	94.3%	93.9%

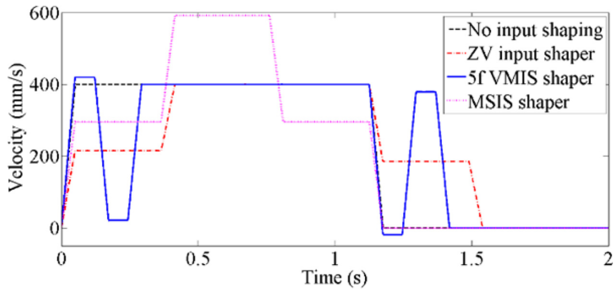


Fig. 8 Two special shaped motion profiles to compensate delayed rise time

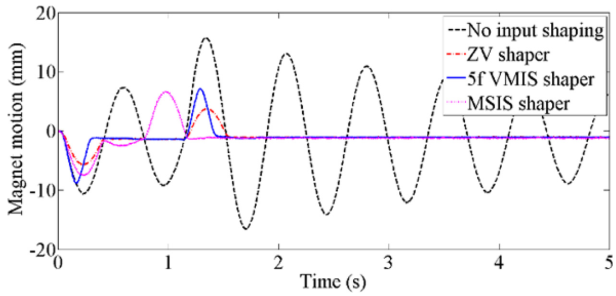


Fig. 9 Magnet track oscillations of two special shaped motion profiles

as shown in Figs. 6(b) and 6(c). Magnet track oscillations and mover in-position errors are quantitatively summarized during and after motion, as shown in Table 3. Magnet track oscillation and mover in-position errors are reduced even during the motion. In addition, the transmitted force is reduced considerably with the shaped input motion profiles because the transmitted force is proportional to the magnet track oscillation. Fig. 7 show the transmitted force for three motion profiles. The transmitted forces are significantly reduced with the input-shaping methods since the magnet track oscillations decreases.

4.2 Compensation of Delayed Rise Time of Input-Shaping

Two special input-shaping methods: 5f virtual mode input shaper (5f VMIS)[12] and max. speed-up input shaper (MSIS)[13] to compensate the delayed rise time of the mover are compared

Table 4 Comparisons of ZV, 5f VMIS and MSIS methods during and after motion

		ZV	5fVMIS	MSIS
During motion	Magnet track oscillation	46.3%	16.8%	67.1%
	In-position error	3.78%	3.0%	29.39%
After motion	Magnet track oscillation	89.9%	92.2%	91.4%
	In-position error	94.3%	91.2%	93.9%

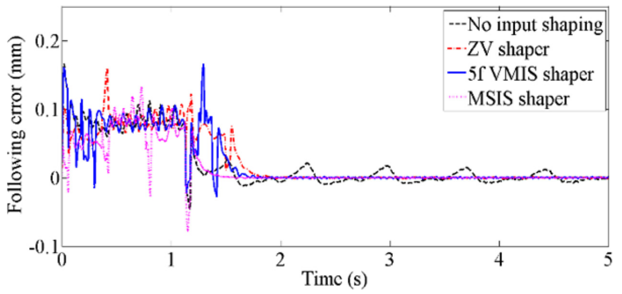


Fig. 10 Mover in-position errors of two special shaped motion profiles

with the original and ZV motion profiles in Fig. 8. ZVD has longer rise time delay than ZV and is not included in comparison. In addition, magnet track oscillations of two motion profiles are compared with those of the original and ZV motion profiles in Fig. 9. Although the magnet track oscillation is larger than ZV input shaper during motions, magnet track oscillations almost disappear after motions. MSIS shows better performance than 5f VMIS in terms of magnet track oscillations.

Mover in-position errors of two motion profiles are compared with those of the original and ZV motion profiles in Fig. 10. In addition magnet track oscillations and mover in-position errors of two input-shaping methods are quantitatively summarized during and after motion, as shown in Table 4. Mover following error of MSIS is smaller than ZV and 5f VMIS both during and after motions. In particular, MSIS shows much better performance than ZV and 5f VMIS in terms of in-position errors.

5. Conclusion

This paper presents input-shaping methods for a linear motor motion stage with a passive RFC mechanism. We built an air-bearing linear motor motion stage with the passive RFC mechanism and investigated effect of input-shaping methods on the linear motor motion stage with passive RFC mechanism by comparing the magnet oscillation and in-position error of the mover. In addition, special input-shaping methods to reduce the rise time delay of the mover are investigated for the linear motor motion stage with the passive RFC. Properly shaped input motion profile such as ZVD or MSIS not only removes residual vibration of the passive RFC mechanism without any additional devices but also reduce transmitted reaction force and in-position error.

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