An Eddy Current Damper for Reaction Force Compensation for a Linear Motor Motion Stage

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***Abstract*—This paper presents an eddy current damper (ECD) for reaction force compensation for a linear motor motion stage. A reaction force compensation mechanism with a movable magnet track and an ECD (or conductor plate) is developed. Lumped model of the ECD is derived considering sinusoidal magnetic flux density distribution and effective width of the ECD. In addition, effects of both the location and width of the conductor plate are discussed. Multi-physical transient analysis of ECD is analyzed using commercial finite element software, which is compared with the lumped parameter analysis. Finally, the derived lumped model is validated with experiments.**

I. INDTRODUCTION

Vibration of the machine base due to reaction force during rapid acceleration or deceleration motion is one of main causes for reducing life and productivity of the system. A large force during accelerating a payload generates an equal opposite reaction force to the system base. This reaction force causes the system to oscillate with unacceptable amplitude or in long settling time, which has a bad influence on production quality of manufacturing process and vibration sensitive device [1]. In addition, the residual vibration of the system base degrades the system productivity since the system cannot precede the next process without attenuating the vibration.

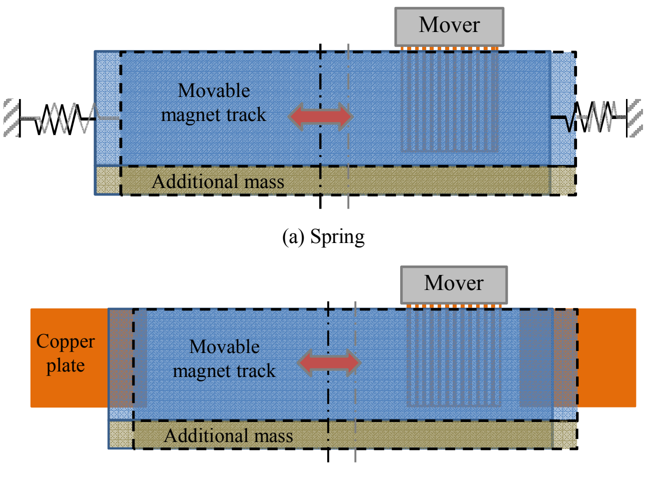
There are two main reaction force compensation (RFC) methodologies to reduce the residual vibration of the system [2-4]. One is to use an isolated mechanical structure for an independent transfer path of the reaction force [2]. The other is using a dummy motion stage to generate counter force and to cancel out the reaction force [3, 4].

A reaction force compensation mechanism with a movable magnet track and an ECD (or conductor plate) is developed. This mechanism relaxes disadvantages of the spring based reaction force compensation mechanism such as resonance and difficulty of assembly and design due to spring [5]. In addition, design conditions such as force transmission ratio and magnet track displacement can be satisfied by adjusting the shape and location of the conductor plate [6].

II. REACTION FORCE COMPENSATION MECHANISM BASED ON ECD

A. Principle

Reaction force compensation systems of moving magnet type based on spring and ECD are shown in Fig. 1. Both reaction force compensation systems consists of movable magnet track with additional mass and restrictor of magnet track displacement (either spring or ECD). In particular, ECD or conductor plate at both end of magnet track generates easily damping force for the magnet track. Desired performance can be achieved by adjusting additional mass and spring or ECD.



(b) ECD

Figure 1. Passove reaction force compensation mechanisms

Reaction force compensation device based on ECD has several advantages compared with that based on spring. Although ECD has nonlinear characteristic related to the displacement of magnet track, reaction force system with ECD has no resonance (due to removing spring), high DOF on design, low cost for assembly and manufacturing. However, design and analysis of the ECD is difficult and there may be a homing problem of magnet track due to friction.

B. Modeling

Both reaction force compensation system can be modeled as Eq. (1) by generalizing the restricted force of either spring or ECD for magnet track as F_r. Magnet track (m_{MT}) with additional mass (m_D) can move (x_{MT}) freely with respect to the machine base (m_{Base}) and either spring or ECD generates restricted force ($f_R(x_{MT}, \dot{x}_{MT})$) for the movement of magnet track. While the restricted force of spring for magnet track can simply be expressed with $f_R = k_S\, x_{MT}$ in case of spring, the restricted force of ECD for magnet track has complex form and will be provided later in detail. Part of reaction force or restricted force is transferred to the machine base through the spring or ECD, as shown in Eq. (1).

$$(m_{MT} + m_D)\dot{x}_{MT} + f_R(x_{MT}, \dot{x}_{MT}) = f_T(t) \qquad (1)$$

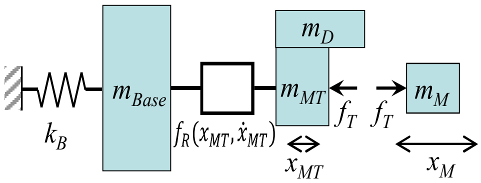


Figure 2. Dynamic model for reaction force compensation mechanism of moving magnet type

C. ECD

Damper force for moving conductor plate in the constant magnetic field can be expressed with Eq. (2) and is proportional to geometric coefficient (α), square of magnetic flux density (B), conductivity (σ), thickness (t), height (l), width (w) and velocity of the conductor (v).

$$F_d = \alpha\sigma t B^2 l w v \qquad (2)$$

Effective with of ECD changes according to movement of magnet track, width and location of the conductor plate, as shown in Fig. 1 (b). If the conductor plate is completely inside of magnet track, the effective width is same as the width of conductor plate irrespective of the displacement of magnet track. However, the effective width of the ECD depends on the displacement of the magnet track if a part of conductor plate is not inside of the magnet track.

Flux density is sinusoidal along motor moving direction. Alternating arrangement of south and north poles produces sinusoidal flux density, which generates thrust force with three phase current of coil.

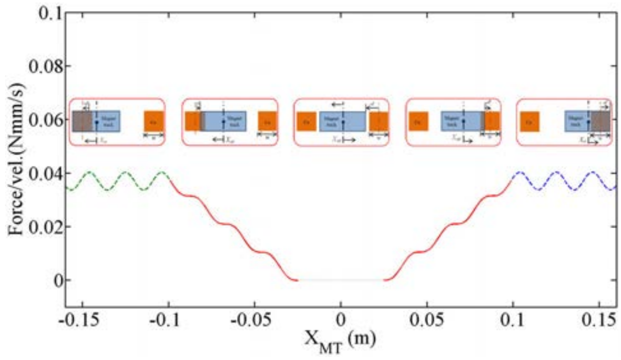
We can calculate ECD force over velocity considering its effective width and sinusoidal magnetic flux density using Eq. (3). The final expression may be different according to displacement of the magnet track. The ECD force over velocity according to the magnet track position can be calculated as shown in Fig. 4.

$$F = \alpha\sigma t l B^2 \int \sin^2\left(\frac{\pi}{p}x\right)dx \qquad (3)$$

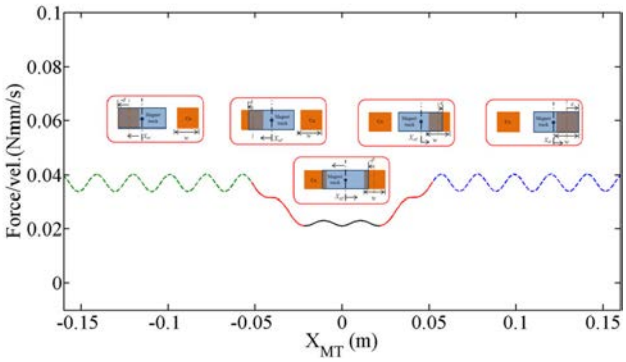
III. Lumped Analysis of Reaction Force Compensation Mechanism Based on ECD

A. Simulation model.

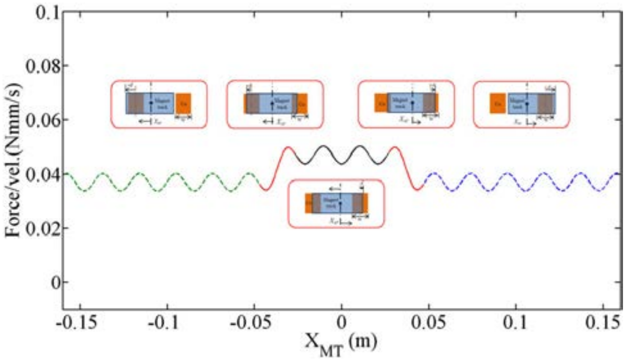
Simulink model for simulation is shown in Fig. 4. Thrust force is calculated considering mover acceleration and guide friction. Then, response of magnet track is calculated with Eq. (1) considering mathematical model of ECD (Eq. (3)) and effective width of ECD, as shown Fig. 4. The linear motor used for simulation has continuous force of 208N and max. velocity of 5 m/s. The sinusoidal variation of the magnetic flux density of magnet track along moving direction is neglected and the geometric coefficient for ECD is determined considering the rectangular shape of magnet [7]. The motion file has each moving distance of 100mm, max. velocity of 500mm/s and max. acceleration of 10m/s^2.



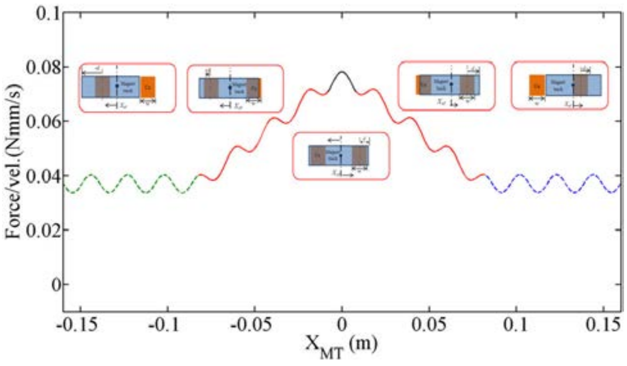
(a) $d<0$, $|-d| > w/2$



(b) $d<0$, $|-d| < w/2$



(c) $d>0$, $|d| < w/2$



(d) $d<0$, $|d| > w/2$

Figure 3. Eddy current force variation according to the magnet track position

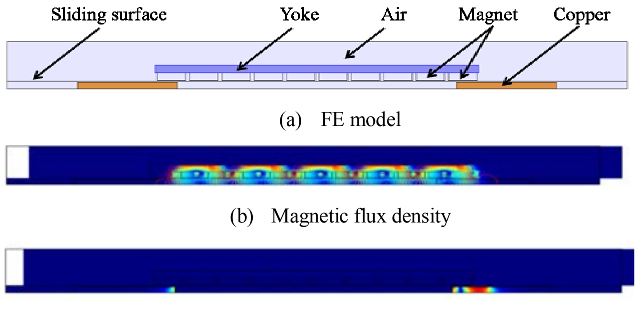


Figure 4. FEM analysis of the ECD with moving magnet track

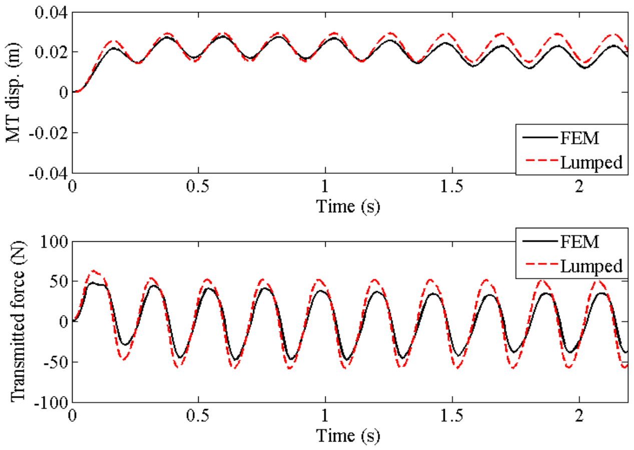


Figure 5. Comparison of Lumped and FEM analyses

B. *Multi-physical analysis of reaction force compensation system*

Finite element model and mesh generation for reaction force compensation system with ECD is shown in Fig. 4 (a). Only half of reaction force compensation system is modeled, which consists of copper plate, permanent magnet, yoke and air as shown in Fig. 4(a). Movement of magnet track is modeled using deformable mesh is used and sliding surface is set as identity pair for fixed and movable geometries. First, static analysis is performed for initial values of transient analysis. Then, magnetic field and motion equation of Eq. (1) are analyzed simultaneously with COMSOL [8]. Static magnetic field analysis is performed at initial position. Then, time-dependent coupled analysis of magnetic field and motion equation of magnet track are performed. Fig. 4 (b) and (c) show magnetic potential distribution and current density of copper plate at 2 s, respectively. The eddy current is induced according to the movement of the magnet track, which produces eddy current damping force interacting with magnetic field.

Magnet track displacement and transmitted force of both lumped and FEM analyses are compared in Fig. 5. The lumped analysis matches quite well with FEM analysis.

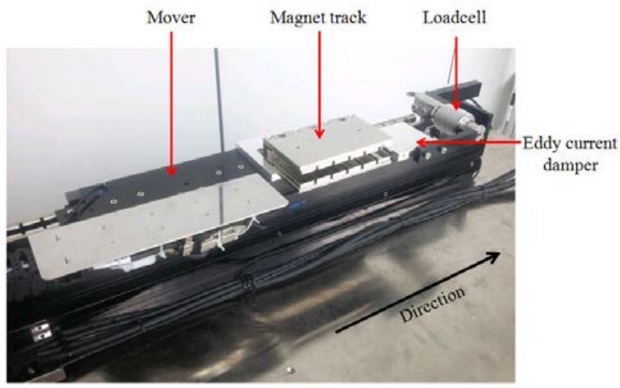


Figure 6. Experimental set-up

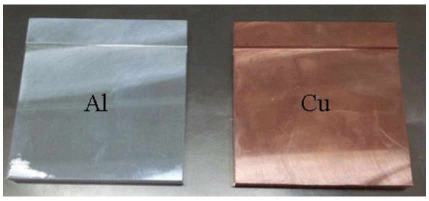


Figure 7. Al and Cu plate for ECD

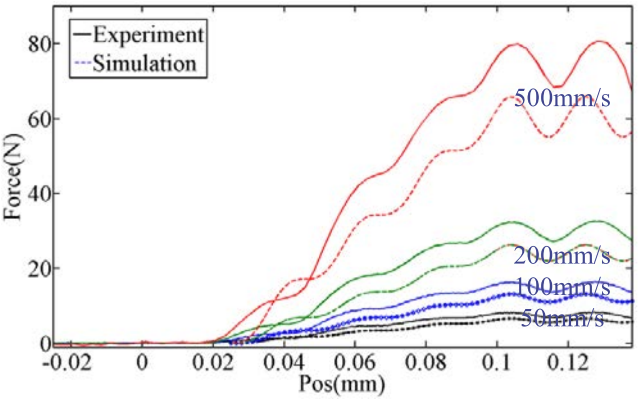
IV. EXPERIMENTAL VALIDATION

A. *Experimental set-up.*

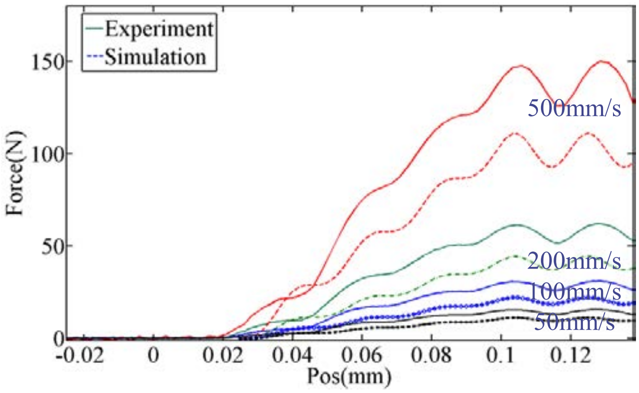
We built an experimental set-up with a linear motor motion stage as shown in Fig. 6 and its specifications are shown in Table I. Experimental set-up consists of a linear motor stage, load cell, magnet track and ECD plate (Al or Cu plate of Fig. 7). The small magnet track is attached on the mover and the ECD plate is assembled with the load cell. The load cell measures eddy current damper force during mover motion.

TABLE I. SPECIFICATION OF EXPERIMENTAL SET-UP

Product	Name		Features or unit	Value
Umac (controller)	Acc-24E2	PWM command output /digital input	phase voltage commands channel	2
			Encoder channel	2
	Acc-51E	Sinoidal encoders	times	4096
			Input Voltage	1
			Input channel	4
	Acc-36E	ADC	Output voltage	±10
			resolution(bit)	12
JSME-02D (Servo Amp)	Peak Output Current		Arms	15
	Input Frequency		Hz	50/60
	Phase Requirement		Phase	1 or 3
	Maximum PWM Frequency		kHz	15
	Minimum Dead Time		µs	3.5
	resolution		bit	12
Loadcell	Rated output		mV/ V	2.0 ± 0.005
	Repeatability		%	0.01
	Max. capacity		kgf	50



(a) Al plate (9 mm thickness)



(b) Cu plate (9 mm thickness)

Figure 8. Comparison of meausred and simulated ECD force

B. *Experimental results.*

Experimental and simulation results are compared in Fig. 8. We generate mover motion with different speed (50, 100, 200 and 500 mm/s) and measure the ECD force of Al or Cu plate. Fringe effect makes large error at the beginning of the magnet track. Although there are mismatches due to ignoring harmonic components of the magnetic flux density, simulation results matches well with the experimental results. In particular, experimental results of the Cu plate has substantial deviation from the simulation results since

V. CONCLUSION

This paper presents an ECD for reaction force compensation for a linear motor motion stage. Lumped model of the ECD is derived considering sinusoidal magnetic flux density and effective width of ECD. In addition, effects of both the location and width of the conductor plate are discussed. Multi-physical transient analysis of ECD is analyzed using commercial finite element software, which is compared with the lumped parameter analysis. Finally, the derived lumped model is validated with experiments.

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