Dynamic Analysis of New Two-DOF Linear Oscillatory Actuator Employing 3-D Finite Element Method

Takamichi Yoshimoto[1], Noritaka Shoji[1], Katsuhiro Hirata[1],
Kenji Ueyama[2], Eiichiro Hashimoto[2] and Takahiro Takagi[3]
[1]Department of Adaptive Machine Systems, Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565-0871, Japan
k-hirata@ams.eng.osaka-u.ac.jp
[2]Sanyo Electric Co., Ltd., 1-18-3, Hashiridani, Hirakata, Osaka, 573-8534, Japan, Kenji.ueyama@sanyo.com
[3]Sanyo Seimitsu Co., Ltd., 1771, Nakamaruko, Ueda, Nagano, 386-0495, Japan, takagit@smt-sanyo.co.jp

Abstract — This paper proposes a new linear oscillatory actuator with two degrees of freedom. The dynamic characteristics of the actuator were demonstrated employing the 3-D finite element method.

I. INTRODUCTION

Recently, linear oscillatory actuators (LOA) have been used in a wide range of applications due to their advantages: high efficiency, simple structure, easy control, and so on [1]. Small-sized LOAs are especially expected to be applied to haptic devices and the vibration system of mobile phones.

In this paper, we propose a new linear oscillatory actuator with thin two degrees of freedom. The dynamic characteristics of the actuator were demonstrated employing the 3-D finite element method.

II. ANALYZED MODEL AND OPERATING PRINCIPLE

The basic structure of our thin Two-DOF Oscillatory actuator is shown in Fig. 1(a). This actuator mainly consists of a stator, a mover and some springs. The stator has two orthogonal coils, and the mover is composed of four magnets, yoke and a high-specific heavy metal weight. The mover can be moved freely in the X-axis and the Y-axis, and each axis is driven independently. When Coil1 is excited, the mover moves in the X-axis direction, and when Coil2 is excited the mover moves in the Y-axis direction.

III. ANALYZED METHOD

A. Magnetic Field Analysis

Using magnetic vector potential $\boldsymbol{A}$, and the current flowing through the coils I_0, the equations of the magnetic field and the electric circuit are coupled and are expressed as follows:

$$rot(\nu rot\mathbf{A}) = \mathbf{J}_0 + \nu_0 rot\mathbf{M} \tag{1}$$

$$E = V_0 - RI_0 - \frac{d\Psi}{dt} = 0 \tag{2}$$

$$\boldsymbol{J}_0 = \frac{n_c}{S_c} I_0 \boldsymbol{n}_s \tag{3}$$

where ν is the reluctivity, $\boldsymbol{J}_0$ is the exciting current density, ν_0 is the reluctivity of the vacuum, $\boldsymbol{M}$ is the magnetization of the permanent magnet, V_0 is the applied voltage, R is the resistance, Ψ is the interlinkage magnetic flux of the excited coil, n_c and S_c are the number of turns and the cross-sectional area of the coil respectively, and $\boldsymbol{n}_s$ is the unit normal vector to the coil's cross section.

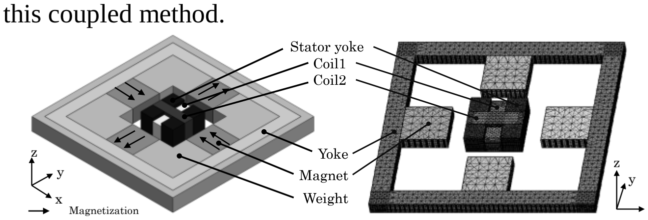
B. Coupled Analysis with Motion Equation

The motion of the mover is described as follows:

$$M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + k_x x = F_x \tag{5}$$

$$M\frac{d^2y}{dt^2} + D\frac{dz}{dt} + k_y z = F_y \tag{6}$$

Where M is the mass of the mover, x and y are the displacement of the movers, F_x and F_y are the magnetic force components, k_x and k_y are the spring coefficients, and D is the viscous damping coefficient. The thrust of the mover is calculated using the Maxwell stress tensor method, and is substituted into equations (5) and (6). At each time step, the finite element mesh is refreshed, and the position and velocity of the mover are calculated by solving the above equations of motion. First of all, four meshes which correspond to the initial and the final shapes of the x and y directions are prepared. The number of elements and nodes of one mesh is the same as the other three meshes. Refreshed coordinate data of each node after movement of the mover is determined by interpolating the initial and the final coordinate data [2]-[5]. Fig. 2 shows the flowchart for this coupled method.



(a)Structure of Actuator (b)FEM model (1/2 region)

Fig. 1. Structure of two-DOF oscillatory actuator

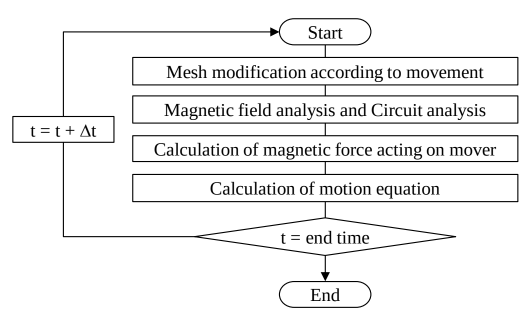


Fig. 2. Flowchart for analysis

TABLE I
ANALYSIS CONDITIONS

Coil1	Voltage (V_{P-P})	1.0
	Resistance (Ω)	5.6
	Number of turns (turn)	94
Coil2	Voltage (V_{P-P})	1.0
	Resistance (Ω)	5.6
	Number of turns (turn)	43
Magnetization of magnets (T)		1.42
Mass of mover (g)		3.15
X-axis spring constant (N/mm)		5.6
Y-axis spring constant (N/mm)		2.8
Viscous damping coefficient (N·s/m)		0.032

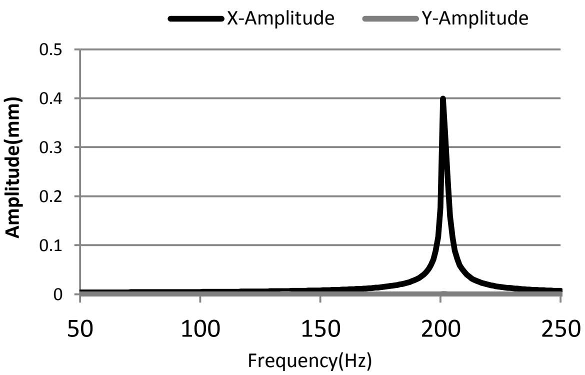


Fig. 3. Resonance characteristics

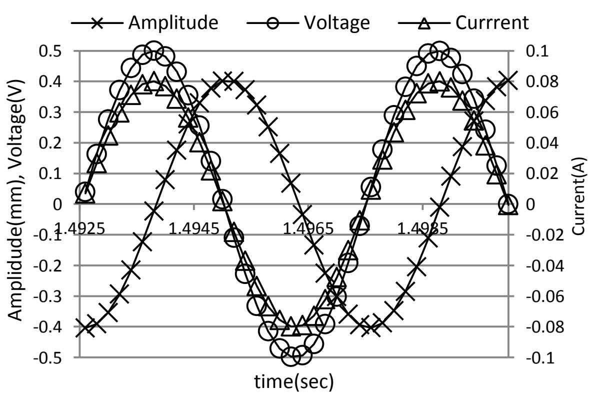


Fig. 4. Calculated steady-state waveforms (201Hz)

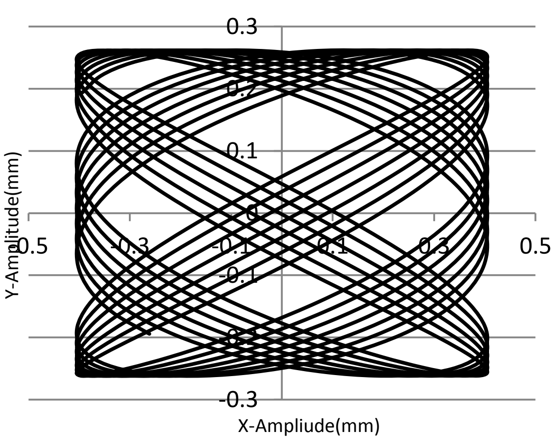


Fig. 5. Trajectory of mover

IV. ANALYZED MODEL AND RESULTS

A. *Analyzed model and condition*

Fig. 1(b) shows the FEM model without the air region and weights. The analyzed region is 1/2 of the whole region because of the symmetry. The number of tetrahedron elements is about 1,032,000, the number of edges is about 1,220,203, and number of unknown variables is about 1,187,949. Table I shows the analysis conditions.

B. *Dynamic characteristics*

Fig. 3 shows the characteristics of the amplitude versus operating frequency when the x-axis coil was excited. The peak amplitude of the calculated result was 0.40mm at 201Hz, and the peak amplitude of the y-axis result was 0.0004mm at 135Hz. The characteristics of the y-axis were also calculated. The peak amplitude of the calculated result was 0.27mm at 135Hz, and the peak amplitude of the y-axis result was 0.0001mm at 135Hz. We can see that the axis does not interfere with each other, and can move independently.

Fig. 4 shows the calculated steady-state waveforms of the voltage and current of the x-axis coil, and the amplitude of the mover when the x-axis coil was excited. We can see that the amplitude phase lags behind the current phase by 90 degrees, which indicates that the mover is resonating. When the y-axis coil was excited, a similar phenomenon was observed.

Fig. 5 shows the calculated trajectory of the mover when the two coils are excited simultaneously. We can see that the mover is able to move to all positions on the X-Y plane.

V. CONCLUSION

This paper proposed a new linear oscillatory actuator with thin two degrees of freedom. The dynamic characteristics of the actuator were calculated employing the 3-D finite element method. As a result, the effectiveness of the actuator was clarified.

VI. REFERENCES

[1] Asai, Y.; Hirata, K.; Ota, T.; , "Dynamic Analysis Method of Linear Resonant Actuator With Multimovers Employing 3-D Finite Element Method," Magnetics, IEEE Transactions on , vol.46, no.8, pp.2971-2974, Aug. 2010

[2] Yamaguchi, T.; Kawase, Y.; Kodama, H.; Hirata, K.; Hasegawa, Y.; Ota, T.; . "Eddy current damping analysis of laser marker using 3-D finite element method," Magnetics, IEEE Transactions on , vol.43, no.4, pp.1011-1014, April 2006

[3] Hirata, K.; Yamamoto, T.; Yamaguchi, T.; Kawase, Y.; Hasegawa, Y.; , "Dynamic Analysis method of Two-Dimensional Linear Oscillatory Actuator Employing Finite Element Method," Electromagnetic Field Computation, 2006 12th Biennial IEEE Conference on , vol., no.,pp.107-107

[4] Yamaguchi, T.; Kawase, Y.; Sato, K.; Suzuki, S.; Hitara, K.; Ota, T.; Hasegawa, Y.; , "Trajectory Analysis og 2-D Magnetic Rezonant Actuator," Magnetics, IEE Transactions on , vol.45, no.3, pp.1732-1735, March 2009

[5] Hirata, K.; Hasegawa, Y.; Ota, T.; Yamaguchi, T.; Kawase, Y.; Eguchi, T.; Kodama, H.; "Dynamic Analysis of Eddy Current Damping Mechanism Employing 3-D Finite Element Method" IEE Japan Trans IA , vol.125, no.12, pp1140-1144, 2005.