Simplified Position Estimation Using Back-EMF for Two-DoF Linear Resonant Actuator

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***Abstract*—This paper proposes a simplified position estimation method and clarifies the dynamic characteristics of the two degree-of–freedom (DoF) resonant actuator under sensorless control. The feature of this two-DOF actuator is that movement in the x and z axis can be independently controlled by vector control. In this paper, we extrapolate the mover position from the zero crossing time and amplitude of the back electromotive force (EMF). During both single and biaxial drive, it was found that the amplitude of the x and z axis could be independently controlled without using position sensors. From these results, the effectiveness of proposed control method was verified.**

***Index Terms*—Finite element methods, Electromagnetic analysis, Actuators, Permanent magnet machines, Sensorless control.**

I. INTRODUCTION

Linear resonant actuators (LRAs) have been used in a wide range of applications because they can reciprocate in a comparatively short stroke in spite of their compact size and light weight. We proposed a two-DOF resonant actuator where both axes can be independently driven under vector control, and also a coupled analysis method for analyzing its dynamic characteristics by combining magnetic field analysis with electric circuit analysis, control method, and its motion equation in our 3-D FEM code[1-2]. The actuator needs a position sensor for vector control but this results in problems such as an increase in parts, cost, and decreased reliability. Various techniques have been proposed for sensorless motor control [3-5], but it is difficult to apply these methods to the proposed two-DoF resonant actuator because this actuator moves in the airgap direction and its reciprocating motion at high frequencies.

In this paper, we propose a simplified position estimation method using the back-EMF of the two-DOF resonant actuator. This approach takes advantage of the constant drive frequency. The effectiveness of proposed method is clarified by 3-D FEM analysis.

II. ANALYZED MODEL AND PROTOTYPE

The basic structure of the two-DOF resonant actuator is shown in Fig. 1. This actuator mainly consists of a mover, a stator and resonance springs in the x and z directions that support the mover. The mover is composed of permanent magnets (NbFeB, Br=1.42 T) and a back yoke. The stator is composed of an E-shaped laminated yoke with three phase excitation coils (45 turns). This actuator is assumed to move with a range of ±1.2 mm in the x direction and ±0.5 mm in the z direction, respectively.

The prototype is shown in Fig. 2. To avoid the influence of friction, the mover is supported by flat springs for movement in the x axis, and is supported by linear bearings for movement in the z direction. The mover can be driven independently in each axis.

III. ANALYSIS METHOD

A. Magnetic Field Analysis

Using the 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:

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

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

$$\boldsymbol{J}_0 = \frac{n_c}{S_c} I_0 \boldsymbol{n_s}\ \cdot \tag{3}$$

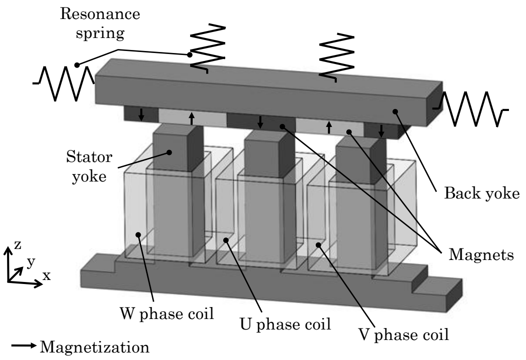

Fig. 1. Basic structure of two-DOF resonant actuator

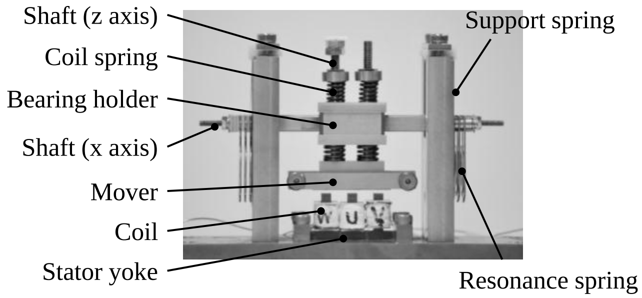

Fig. 2. Prototype of two-DOF resonant actuator

where ν is the reluctivity, $\boldsymbol{J}_0$ is the excitation 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 of the coil's cross section.

B. *Coupled Analysis with Motion Equation*

The motion equation of the mover is shown as follows.

$$M_x \frac{d^2 x}{dt^2} + D_x \frac{dx}{dt} + k_x z = F_z \cdot \tag{4}$$

$$M_z \frac{d^2 z}{dt^2} + D_z \frac{dz}{dt} + k_z z = F_z \cdot \tag{5}$$

where M_x and M_z are the mass components of the mover. The mass has the x and z components due to difference in the support structure. x and z are displacements of the mover in the x and z directions, D_x and D_z are the viscous damping coefficients, k_x and k_z are the spring constants in the x and z directions, and F_x and F_z are the electromagnetic forces acting on the mover in x and z directions, respectively.

The thrust of the mover is calculated using the Maxwell stress tensor method, and is substituted into equations (4) and (5). The position of the mover is calculated at each time step. Vector control is taken into consideration in this analysis.

C. *Position Estimation Method*

In this paper, the position of the mover is estimated from the back-EMF. The circuit equation of one phase is shown as follows.

$$E - Ri - L\frac{di}{dt} - k_e \omega = 0 \tag{6}$$

where E is the phase voltage, R is the resistance, L is the inductance of the coil, i is the phase current, k_e is the back-EMF constant and ω is the velocity of mover.

Only the x axis position is required for vector control. It can be obtained by inputting the x component of the mover velocity into the motion equation.

However, the z component of the mover velocity is included in the back-EMF. In the proposed actuator, it is comparatively easy to separate the x component of the mover velocity from the back-EMF using a filter because of the constant drive frequency in steady state. Fig. 3 shows the FFT analyzed result of the back-EMF of the V phase under biaxial drive. Fig. 4 shows the relationship between the peak value of the x component of the back-EMF(V_{EMFMAX}) and displacement amplitude of the x axis. From these results, the displacement of x axis is estimated by the following equation.

$$x^*(t) = f(V_{EMFMAX}) \sin(\omega(t - t_{cross}) + \theta) \tag{7}$$

where f is a function of the back-EMF, t_{cross} is the zero crossing time of the back-EMF, and θ is the phase compensating angle.

IV. RESULTS AND CONCLUSION

Fig.5. shows the analyzed results of the displacement of the mover and estimated displacement under steady state. Here, the x axis is driven by a force of 0.15N, and the z axis is not driven. As can be seen, there is almost no difference between calculated and estimated displacement. The displacement of the calculated result was 1.18 $\mathrm{mm}_{\mathrm{p\text{-}p}}$, and the amplitude of the simulated result was 1.05 $\mathrm{mm}_{\mathrm{p\text{-}p}}$. This small error is caused by the approximation error of the relationship between the peak value of the x component of the back-EMF and the approximation error of the inductance.

It was also found that movement in the x-axis caused the mover to vibrate a little in the z-axis. This interference is thought to be caused by mechanical structural problems and the detent force.

From these results, the proposed simplified position estimation method of the two-DoF resonant actuator under sensorless control was verified and its dynamic characteristics were clarified.

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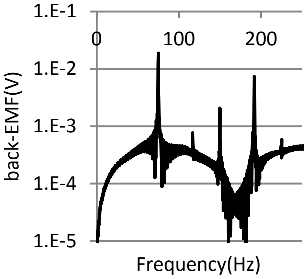

Fig. 3. FFT results of V phase back-EMF(biaxial drive)

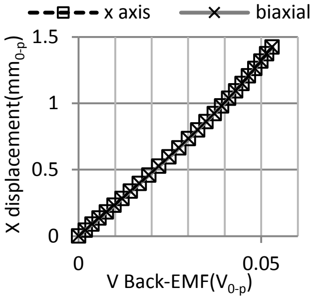

Fig. 4. Relationship between peak value of x component of back-EMF

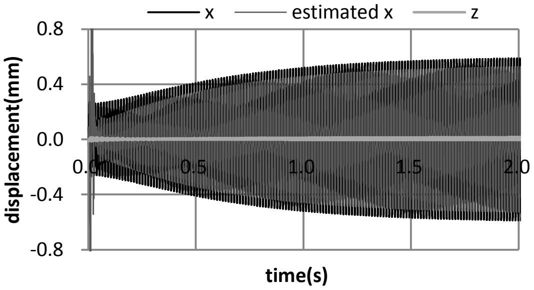

Fig. 5. Analyzed results