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# Asymmetric Acceleration Drive Using Linear Oscillatory Actuator under Open-Loop Control

***Abstract**. This paper proposes an asymmetric acceleration drive method for linear oscillatory actuators under open-loop control. The effectiveness of this method is confirmed through the comparison of the 3-D FEM analysis results with the measurements of a prototype.*

***Streszczenie.** W artykule przedstawiono asymetryczne urządzenie oscylacyjne dla liniowych aktuatorów ze sterowaniem otwarto-pętlowym. Efektywność metody analizy została potwierdzona poprzez porównanie analizy elementowo-skończeniowej z wynikami pomiarów3D (**Asymetryczny przyspieszający napęd wykorzystujący liniowy aktuator oscylacyjny prze otwarto-pętlowym sterowaniu)** ).*

**Keywords:** linear oscillatory actuator, finite element analysis, .
**Słowa kluczowe:** liniowy actuator oscylacyjny, metoda elementów skończonych

## Introduction

Recently, linear oscillatory actuators (LOAs) have been used in a wide range of applications because they have a lot of advantages; high efficiency, simple structure, easy control, and so on [1]. Small-sized LOAs are especially expected to be used as vibration actuators to provide haptic sensation to handheld devices such as recent super-compact mobile phones.

Haptic feedback devices that employ vibration have been designed recently [2]-[5]. In addition, devices that generate a force vector using asymmetric acceleration were studied [6]-[9]. However, these devices are not suitable for incorporation into mobile devices because these devices have problems with size and complexity of control.

In this paper, we propose an asymmetric acceleration drive generation method for small-sized LOA's under open-loop control. The dynamic characteristics of the actuator are calculated by coupling the magnetic field analysis with the motion analysis and employing 3-D FEM. The effectiveness of this drive method under open-loop control is confirmed through the comparison of the measurements of a prototype.

## Basic Structure and Operating Principle

The basic structure of the LOA in this study is shown in Fig. 1. This actuator mainly consists of a mover which is composed of two parallelly magnetized semicircular magnets and a high density metal weight, a stator which is composed of a cylindrical back yoke and an excitation coil, and a spring. The mover mass and the spring constant are 1.81g and 1.93N/mm, respectively. The spring and the case are made of non-magnetic stainless steel.

The operating principle of the LOA is shown in Fig. 2. The magnetic flux from the permanent magnets flows to the center. When the coil is excited, it experiences a Lorentz force due to the interaction between the current flowing through it and the flux from the permanent magnets. However since it is fixed to the back yoke, the resulting reaction force drives the mover in the opposite direction of the Lorentz force. A reciprocating motion is simply created by applying an alternating current to the coils.

## Analyzed Method

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:

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

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

(3) $$\boldsymbol{J}_0 = \frac{n_c}{S_c} I_0 \boldsymbol{n}$$

where $\nu$ is the reluctivity, $\boldsymbol{J}_0$ is the excitation current density, $\nu_0$ is the reluctivity of the vacuum, $\boldsymbol{M}$ is the magnetization of the permanent magnet, $\boldsymbol{V}_0$ is the applied voltage, $R$ is the resistance, $\Psi$ 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 $n_s$ is the unit normal vector of the coil's cross section.

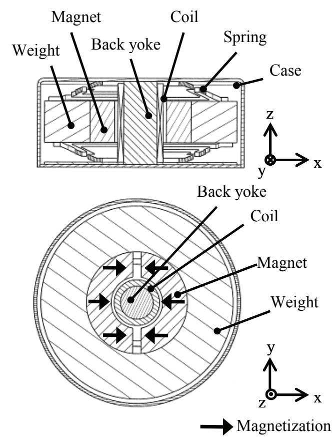



Fig.1. Basic structure of LOA

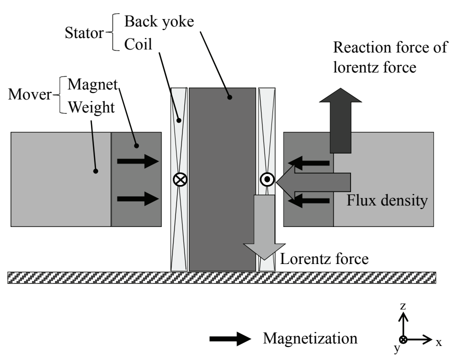



Fig.2. Operation principle

**Coupled Analysis with Motion Equation**

The motion of the mover is described as follows:

$$M\frac{d^2x}{dt^2}+D\frac{dx}{dt}+k_z z=F_z \tag{4}$$

Where $M$ is the mass of the mover, $z$ is the displacement of the mover, $F_z$ is the magnetic force component, $k_z$ is the spring coefficient, and $D$ is the viscous damping coefficient. The thrust of the mover is calculated using the Maxwell stress tensor method, and is substituted into equation (4). At each time step, the finite element mesh is refreshed, and the position and velocity of the mover are calculated by solving the above equation of motion.

Fig. 3 shows the flowchart for the coupled analysis. In this analysis, the mover can be moved a large distance without mesh distortion by using the mesh coupling method [10], which greatly reduces the computation time.

**Analyzed Model and Condition**

Fig. 4 shows the 3-D finite element mesh of the magnetic circuit with the air layers omitted from the diagram. The analyzed region is 1/4 of the whole region because of the symmetry. The mover is moved from -0.8 mm to 0.8 mm. The number of tetrahedron elements, edges, and unknown variables are 225,324, 275,596, and 250,403, respectively.

**Voltage generation for open-loop control**

To generate an asymmetric vibration under open-loop control, the required voltage must be calculated.

First, the flux, inductance, thrust constant, and detent force of the LOA is calculated using 3D-FEM and input into the MATLAB/Simulink model shown in Fig. 5.

Then, a qualitatively similar position-time waveform created by the slider crank [6] was input as the target value. The amplitude of the waveform was different from that of slider crank due to the different stroke lengths of both devices. The force required to move the actuator accordingly was then calculated. Next, the current required to generate the necessary force to move the mover was calculated based on the thrust and the detent characteristic and the mover's present position. Finally, the voltage is calculated. When this voltage is input into the LOA, the same vibration as the target waveform is generated under open-loop control.

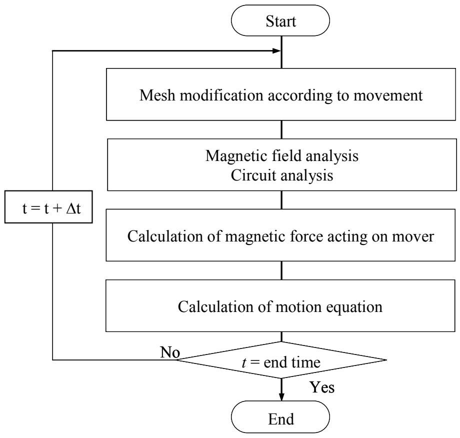



Fig.3. Flow chart for analysis

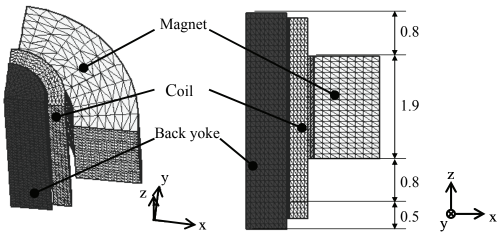



Fig.4. FEM model (1/4 region)

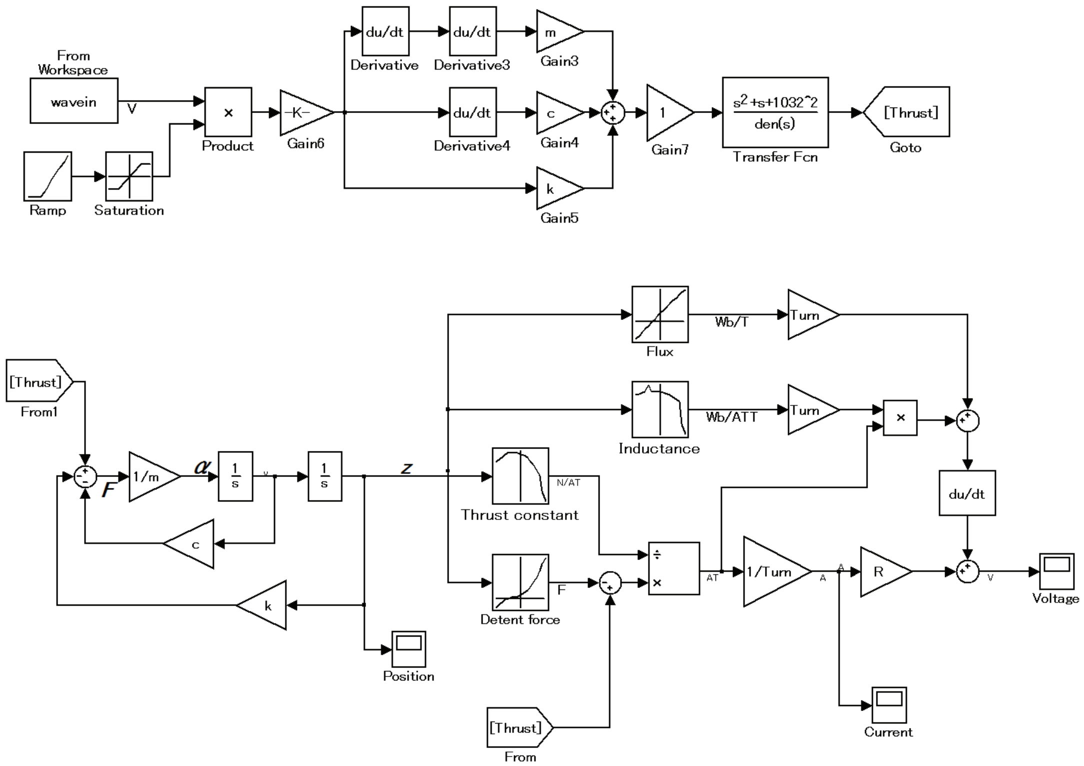
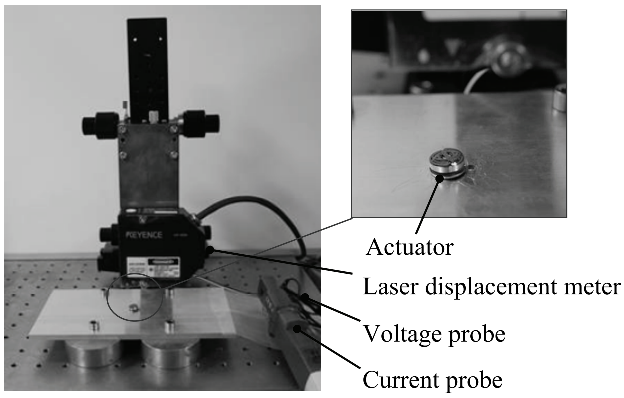



Fig.5. An example of the wide figure inserted into the text

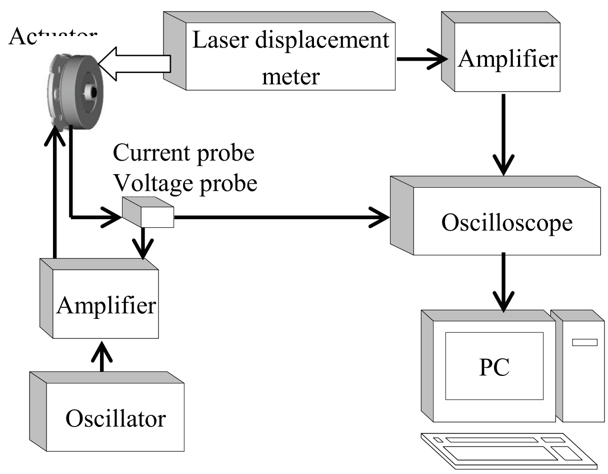
## Results and Discussion

Fig. 6 shows the experimental setup for measuring the mover amplitude. Fig. 7 shows the calculated and measured results of the steady-state mover acceleration when the LOA was operated at a frequency of 10Hz. An asymmetric acceleration similar to the one produced by Amemiya et al [6] was obtained. From these figures, the measured results qualitatively agree with the calculated results though the peak value of the acceleration is different. Moreover, some vibration can be observed in the acceleration waveform of the measured results.

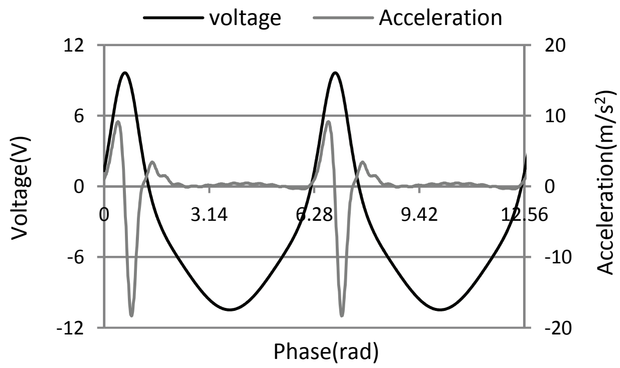
We then attached the LOA to a resin block, and performed an experiment to see if a force vector could be detected. The experimental setup for measuring the acceleration is shown in Fig. 8. We used a 140g block to simulate a handheld device, and suspended the block with a thread to remove influence of friction. The results are shown in Fig.9. It shows that asymmetric acceleration was not detected, and only natural vibration was detected. This was because the generated force was too small for the 140g resin block.



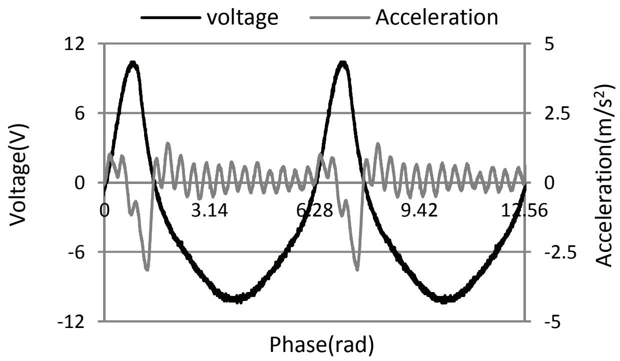

(a) Photograph




(b) Measuring system
Fig.6. Experimental setup




(a) Calculated results




(b) Measured results
Fig.7. Steady-state waveform of input voltage and acceleration (frequency: 10Hz)

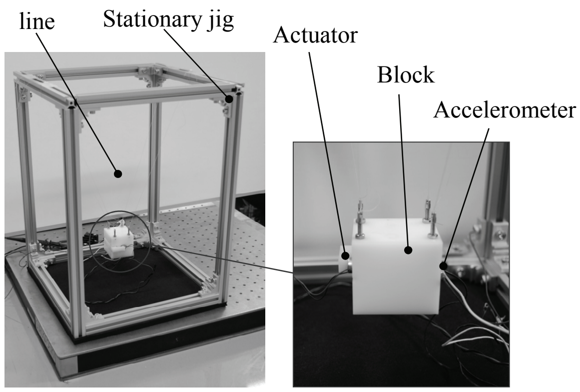



Fig.8.Experimental System

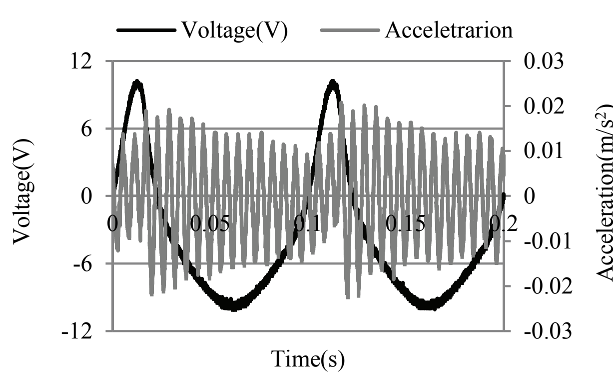



Fig.9.Block acceleration

## Conclusion

In this paper, an asymmetric acceleration drive method for an LOA under open-loop control was presented. The effectiveness of this drive method was verified through 3-D FEM analysis and measurement of the prototype. We succeeded in the generation of asymmetric vibration using an LOA under open-loop control. However we were not able to feel the force vector because the force of the LOA was too small. We aim to correct this problem in the near future.

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] H. Ando, T. Miki, M. Itani, T. Meda, "SmartFinger : Nail-Mounted Tactile Display" , ACMSIGGRAPH 2002 Conference Abstracts and Applications, p. 78, 2002.

[3] H. Wakisaka, M. Ezawa, H. Kato, W. Yoshimura, H. Ito, N. Fukuda, K. Matsuhiro, "Development of high-performance millimeter-size vibrator for cellular phones" , Journal of Magnetism and Magnetic Materials, vol. 242-245, pp. 1195-1197, 2002.

[4] Dongseok Ryu, Gi-Hun Yang, and Sungchul Kang. T-Hive: Vibrotactile Interface Presenting Spatial Information on Handle Surface. IEEE 2009 International Conference on Robotics and Automation. Kobe, Japan, pp 683-688, May 12-17, 2009

[5] Gi-Hun Yang; Moon-sub Jin; Yeonsub Jin; Sungchul Kang; , "T-mobile: Vibrotactile display pad with spatial and directional information for hand-held device," Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on , vol., no., pp.5245-5250, 18-22 Oct. 2010

[6] Amemiya, T.; Maeda, T.; , "Asymmetric Oscillation Distorts the Perceived Heaviness of Handheld Objects," Haptics, IEEE Transactions on , vol.1, no.1, pp.9-18, Jan.-June 2008

[7] Tomohiro Amemiya, Hisashi Sugiyama, "Orienting Kinesthetically: A Haptic Handheld Wayfinder for People with Visual Impairments", ACM Transactions on Accessible Computing, Vol. 3, No. 2, Article 6, pp. 1-23, November 2010.

[8] Tappeiner, H.W.; Klatzky, R.L.; Unger, B.; Hollis, R.; , "Good vibrations: Asymmetric vibrations for directional haptic cues," EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint , vol., no., pp.285-289, 18-20 March 2009

[9] N. Nakamura.; Y. Fukui.; , "Development of Non-grounding Force and Torque Interface" Transactions of the Virtual Reality Society of Japan, Vol.11, No.1, pp.87-90, 2006

[10] T. Ota, Y. Kawase, K. Hirata, Y. Mitsutake: "3-D Eddy Current Analysis of Linear Solenoid Using A New Auto Mesh Coupling Method", IEEJ Transaction on Industrial Applications vol. 119-D, No. 11 pp. 1393-1400, 1999.



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