Development of a two degrees-of-freedom linear oscillatory actuator for vibration control**

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In automobiles, several mechanical parts generate undesirable multidimensional vibrations, which are usually actively controlled by using one degree-of-freedom (DOF) linear oscillatory actuators. This paper proposes a 2-DOF linear oscillatory actuator to realize active control with high vibration control performance and downsizing. First, the design specifications, basic construction, and operation principle were established. Finite element analysis and MATLAB/Simulink were used to confirm that the resulting characteristics satisfied the specification requirements. Finally, the characteristics determined using a prototype were compared with those determined in the analysis.

Keywords: dynamic characteristics, inertial force, multiple degrees-of-freedom

1. Introduction

An automobile is a multimode system that generates undesirable multidimensional vibrations. To improve the noise vibration and harshness performance, active vibration control devices have been developed for automobiles;[1] for example, active control engine mounts, active suspensions, and inertial mass shakers. Conventional devices can reduce only one-dimensional vibrations, although some devices are equipped to reduce multidimensional vibrations. However, the vibration control performance of the former devices is not sufficiently high, and the latter devices involve a complex system.

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[1] Svaricek, F., Bohn, C., Marienfeld, P., Karkosch, H.J. & Fueger, T. *Automotive Applications of Active Vibration Control*, pp. 303–318. IntechOpen (2010).

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Commonly, for applications other than automobiles, additional masses are installed on the mover to increase the inertial force of one degree-of-freedom (DOF) inertial mass shakers; however, in automobile applications employing additional masses should be avoided to reduce the weight of the vehicle.[2] In a previous study,[3] a 2-DOF inertial mass shaker using a 2-DOF linear oscillatory actuator was developed, which could actively control two-dimensional vibrations on a tower structure. When the actuator drives in one direction, however, unnecessary force is generated in the other direction.

Therefore, we have striven to develop a simple 2-DOF inertial mass shaker that generates an independent 2-DOF inertial force without employing additional masses for reducing undesirable and two-dimensional vibration in automobiles. Especially, we focused on the reduction of steady frame vibrations transmitted from an engine. 2-DOF acceleration of vibrations was measured by single- or multi-axis accelerometers. The target 2-DOF inertial force was determined to minimize the acceleration by a least-mean-squares adaptive filter. Then, the inertial force was generated by a 2-DOF actuator with feedback and feedforward control.

In this paper, the development of a novel 2-DOF linear oscillatory actuator with two movers for the device is reported. Its characteristics were verified using the finite element method (FEM) and carrying out measurements corresponding to a prototype.

2. Two-DOF linear oscillatory actuator for vibration control

First, a target inertial force was set as a sinusoidal wave with amplitude 30 N and frequency 25–100 Hz in two dimensions; the limiting current was 3 A. To achieve the target without employing additional masses, a large mover's acceleration should be generated with a large stroke. Thus, the weight and stroke of the target mover were set as 300 g and 10 mm, respectively. The target thrust constant, which is the ratio of the electromagnetic thrust to the applied current, was 10 N/A. For better control, the electromagnetic thrust generated when the position of the mover changes with constant current should be constant.

The developed actuator is shown in Fig. 1. The external dimensions of the main part were 78 × 78 × 61 mm. The proposed actuator consisted of eight springs, a stator and two movers named X and Y. Four springs were connected between the X mover and the stator, and the other four springs were connected between the Y mover and the stator. The stator was composed of two types of coils, labeled X and Y; yokes were made of soft iron; and support parts made of nonferromagnetic materials. The X mover was composed of yokes, eight square-shaped permanent magnets, support parts and linear bearings that provide support on the y and z axes. The Y mover had the same structure as that of the X mover. Magnets magnetized in the positive and negative z directions were alternately attached at the surface of the mover yoke, as shown in Figs 1 (b) and (c). A surface-permanent-magnet-type actuator can generate electromagnetic thrust even for a simple structure. To maintain constant thrust against a large stroke, the relationships between

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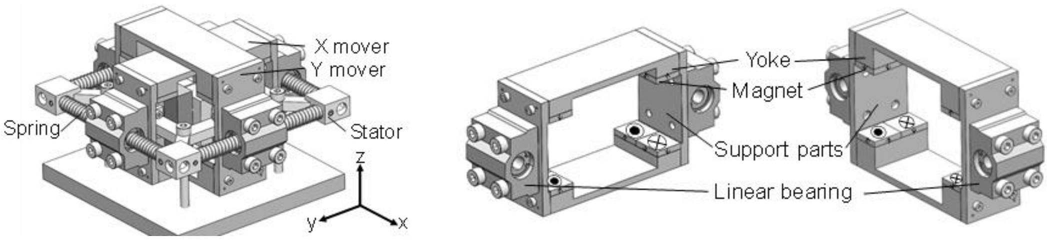
[2] Kraus, R., Millitzer, J., Hansmann, J., Wolter, S. & Jackel, M. Experimental study on active noise and active vibration control for a passenger car using novel piezoelectric engine mounts and electrodynamic inertia mass actuators. *Proc. 25nd Intl Conf. on Adaptive Structure and Technologies* (2014) #048.

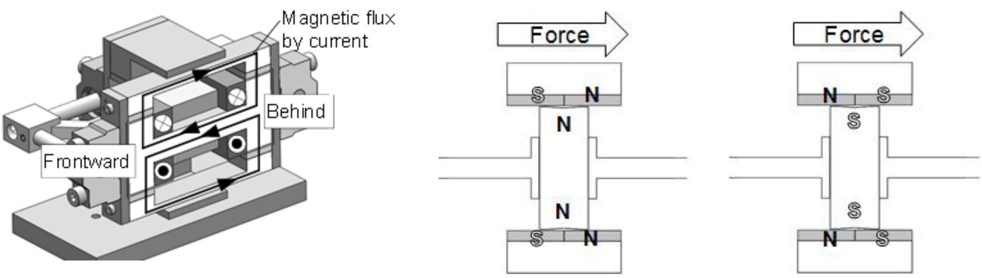
[3] Ezure, K., Yamashita, S. & Sawatari, K. Vibration control of tower structure by a two-dimensional active dynamic absorber. *Proc. 1st Intl Conf. Motion and Vibration Control* (1992) pp. 80–85.

the magnets and stator yoke are determined by referring to those for a 1-DOF actuator,[4] and isosceles triangle-shaped notches were made at the surface of the stator yoke. The operational principle is shown in Fig. 2. The stator yoke facing the X mover is magnetized as the N-pole at the front and S-pole at the back when current is applied to the X coil, and the magnets of the X mover are repulsed by and attracted to the stator yoke; consequently, the X mover is moved, and the Y-mover is moved in a similar manner.Therefore, the actuator can two-dimensionally generate a net thrust at a large stroke. The X and Y movers are mechanically and electromagnetically independent.



(a) (b) (c)

Figure 1. Basic construction: (a) complete; (b) X mover; (c) Y mover.



(a) (b) (c)

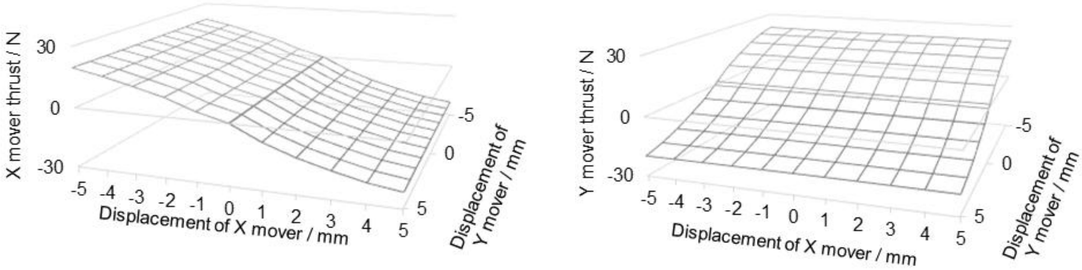
Figure 2. Operational principle: (a) side; (b) front; (c) behind.

3. Static and dynamic analyses

The static thrust pertaining to different positions of the movers was computed using 3D FEM. Fig. 3 shows the detent thrust when no current is applied. The detent thrust of the X mover is nearly in proportion to the position of the X mover and independent of the position of the Y mover. Similarly, the detent thrust of the Y mover is nearly in proportion to the position of the Y mover and independent of the position of the X mover. Figs 4 and 5 show the current thrust when 1 A d.c. current is applied to the X or Y coils. The current thrust is generated only on the X mover when current is applied to the X coil, and vice versa. These results indicate that the static characteristics of the X and Y mover are magnetically independent. The average current thrusts on the X and Y movers at 1 A d.c. were respectively10.8 and –11.6 N, which satisfied the requirement of a target thrust constant of 10 N/A at the target stroke of 10 mm. In addition, the

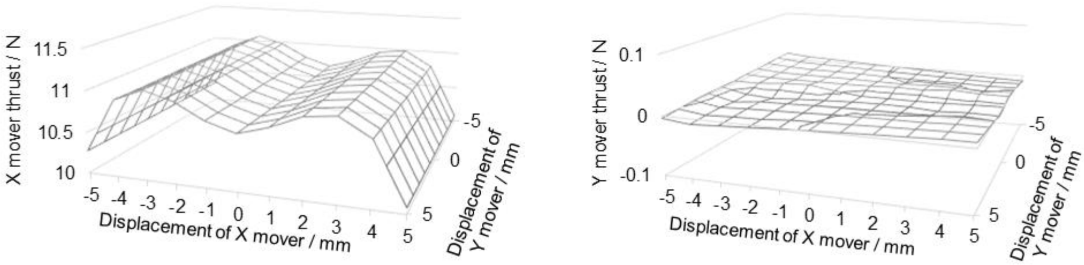
[4] Asai, Y., Hirata, K. & Ota, T. Dynamic analysis method of linear resonant actuator with multimovers employing 3-D finite element method. *IEEE Trans. Magnetics* **46** (2010) 2971–2974.

differences between the maximum and minimum thrust values for the X and Y movers were, respectively, 1.00 and 1.02 N, which are extremely small values compared to the average current thrust. Therefore, the thrust was considered to be independent of the mover's position.



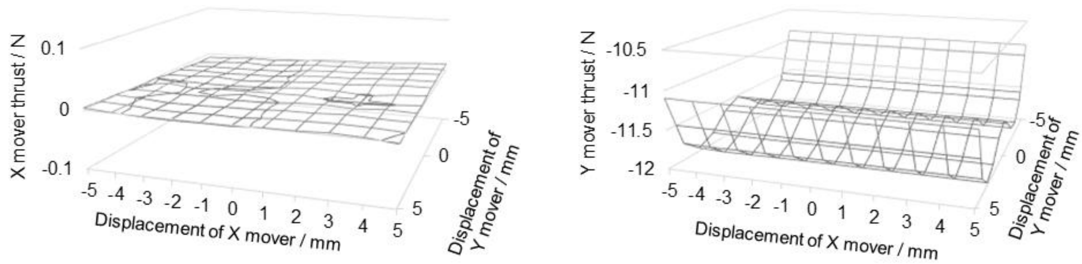
(a) (b)

Figure 3. Analysed detent: (a) X mover; (b) Y mover.



(a) (b)

Figure 4. Analysed current thrust when current is applied to X coil: (a) X mover; (b) Y mover.



(a) (b)

Figure 5. Analysed current thrust when current is applied to Y coil: (a) X mover; (b) Y mover

Next, the dynamic characteristics when applying sinusoidal current were computed using MATLAB/Simulink,[5] Assuming that the two movers are independently driven, the mover positions can be calculated using the following motion equations:

$$m_i \frac{\mathrm{d}^2 x_i(t)}{\mathrm{d}t^2} = K_{Ai}(x_i(t), I_i(t)) I_i(t) + f_{di}(x_i(t)) - c_i \frac{\mathrm{d}x_i(t)}{\mathrm{d}t} - k_i x_i(t) \tag{1}$$

[5] Kitayama, F., Hirata, K. & Sakai, M. Proposal of a two movers linear oscillatory actuator for active control engine mounts, *IEEE Trans. Magnetics* **49** (2013) 2237–2240.

where suffix I expresses the X or Y movers; $x_i(t)$ and $I_i(t)$ respectively denote the position of the mover and the current applied to the coil; m_i, c_i and k_i denote the weight of the mover, damping coefficient and mechanical spring constant; $K_{Ai}(x_i(t), I_i(t))$ and $f_{di}(x_i(t))$ are respectively the thrust constant and detent thrust, which are defined as functions of one or two variables derived from the static analysis results. The hysteresis of soft magnetic material was not considered in this analysis. Sinusoidal current with an amplitude of 1 or 3 A and frequency of 25–100 Hz was applied to the X and Y coils separately. As shown in Figs 6 and 7, the inertial force attains the target value at a low applied current in the low frequency range because of mechanical resonance, and the target value of the inertial force for the movers is attained at an applied limiting current of 3A in the complete frequency range.

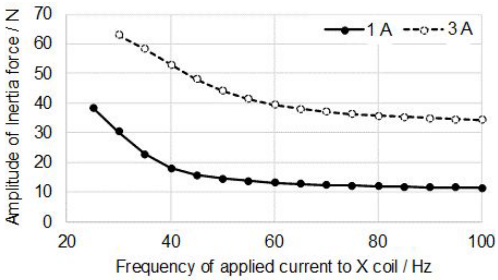


Figure 6. Analysed inertia force for X mover.

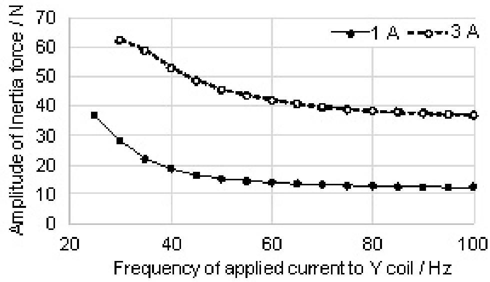


Figure 7. Analysed inertia force for Y mover.

The time variations of the X mover's position and inertial force are shown in Fig. 8. The inertial force was a sinusoidal wave, which is desirable for easy control of the inertial mass shakers.

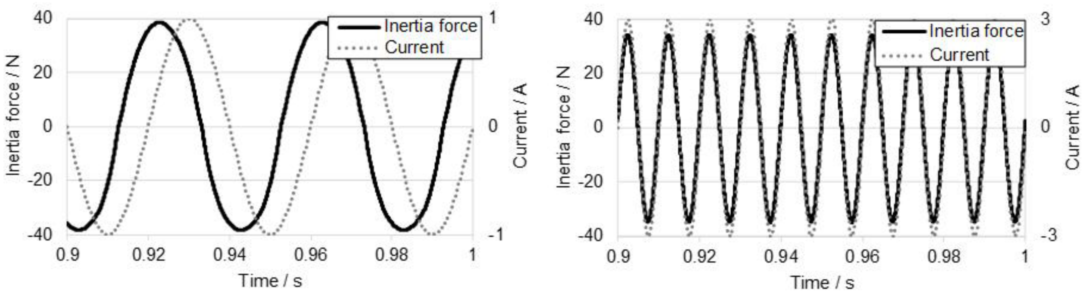


Figure 8. Analysed time variation of current and inertial force on X mover. Amplitude and frequency of current are, respectively: (a) 1 A, 25 Hz; (b) 3 A, 100 Hz.

4. Experimental evaluation using a prototype

A prototype was manufactured to experimentally evaluate the characteristics, as shown in Fig. 9. The weight of movers X and Y was 268 and 328 g, respectively. The experimental setup is shown in Fig. 10. First, the static thrust was measured using a force gauge while the position was determined using a displacement meter. The thrust on one mover was measured when the mover position shifted from +5 to –5 mm and the other mover was held in the initial position by springs. The measured passive force when current was not applied, which is the sum of the detent and mechanical spring forces, is shown in Fig. 11. The measured force was in agreement with the analysed force. Fig. 12 shows the measured current thrust when 1 A of d.c. was applied to the X or Y coils. Current thrust was generated on each mover when current was applied to each coil. The average thrust was 9.11 N for the X mover and –8.94 N for the Y mover, and these values were respectively 15 and 23% smaller than the analysed values. In addition, the differences between the maximum and minimum thrust values were 5.95 and 5.25 N for the X and Y movers, which indicates that the constancy of the measured current thrust was lower than that obtained in the analysis, likely due to an assembly error.

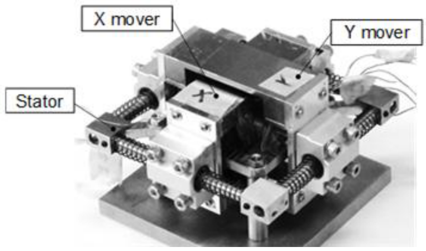


Figure 9. Prototype.

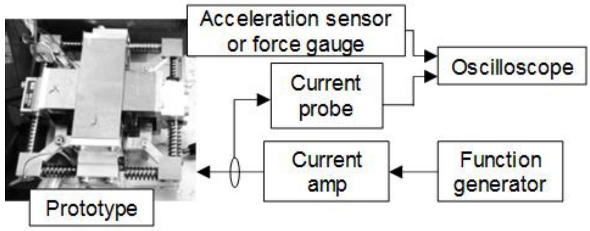
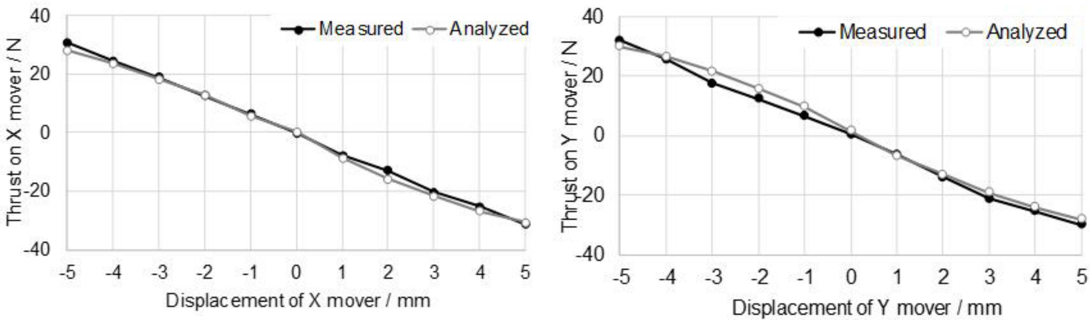
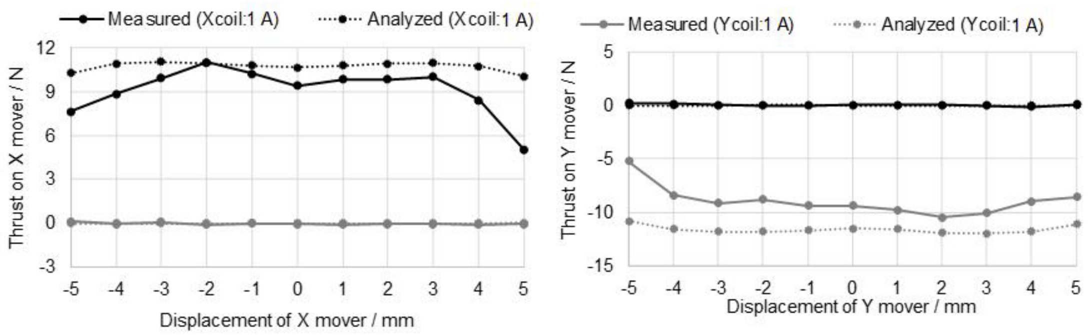


Figure 10. Experimental setup.



(a) (b)

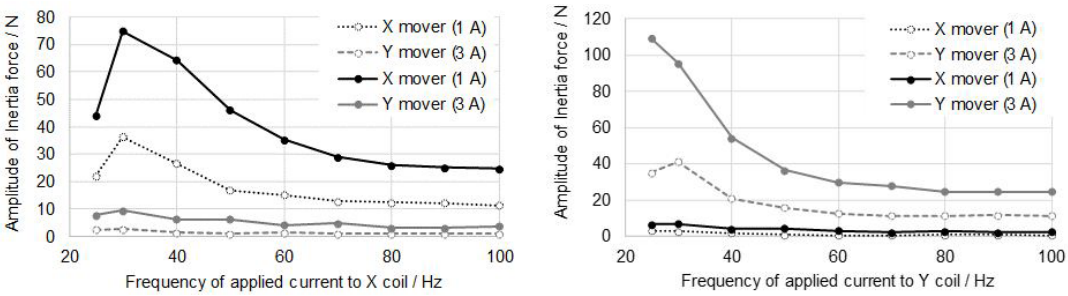
Figure 11. Measured passive force: (a) X mover; (b) Y mover.



(a) (b)

Figure 12. Measured current thrust: (a) X mover; (b) Y mover.

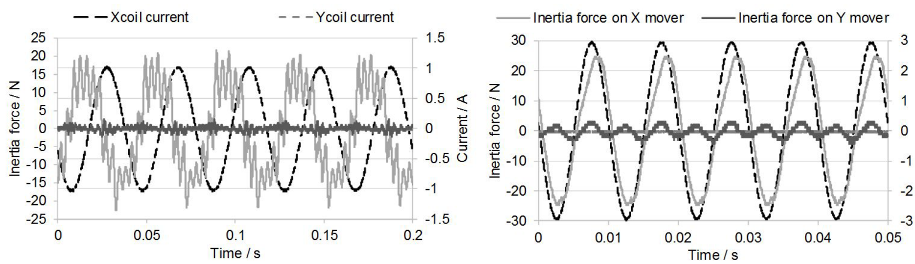
Sinusoidal current was applied to the coils by using a function generator and a current servoamplifier. The acceleration in the two movers was simultaneously measured using two single-axis accelerometers while the current in the two coils was measured using current probes and an oscilloscope. The inertial force was calculated as the product of the measured acceleration and weight. The amplitude of the inertial force when sinusoidal current was applied to the X and Y coils is shown in Fig. 13. The current had an amplitude of 1 or 3 A and a frequency of 25–100 Hz.The inertial force on the X mover was generated primarily when current was applied to the X coil, and that on the Y mover was generated mainly when current was applied to the Y coil. The amplitude of the inertial force was large in the lower frequency range owing to mechanical resonance. However, the inertial force was approximately 35% smaller than the analysed value at a high drive frequency (100 Hz) owing to the lower static current thrust, eddy current, and Coulomb friction.



(a) (b)

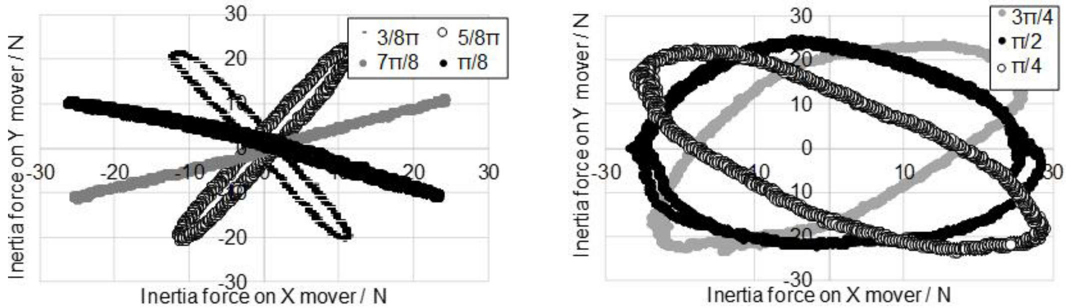
Figure 13. Dynamic inertial force calculated from measured acceleration when current was applied to (a) the X coil; (b) the Y coil.

The time variation of the inertial force and current is shown in Fig. 14. Harmonics of the third, fourth and fifth orders were observed only at a low drive frequency, owing to the mechanical vibrations of the cage and balls in the linear bearings. Furthermore, the current amplitude, frequency and phase difference of the current were set as 3cosθ A, 100 Hz and 0 rad for the X coil and 3sinθ A, 100 Hz and 0 rad for the Y coil. θ was assigned values of π/8, 3π/8, 5π/8 and 7π/8 rad. Subsequently, the amplitude, frequency and phase difference between currents were set as 3A, 100 Hz and ϕ for both coils, where ϕ was assigned values of π/4, π/2 and 3π/4 rad. The inertial force when such current is applied is shown in Fig. 15. The inertial force can be linearly generated for each two-dimensional direction, or elliptically generated.



(a) (b)

Figure 14. Measured time variation of current and inertial force on movers. Amplitude and frequency of current were, respectively (a) 1 A, 25 Hz; (b) 3 A, 100 Hz.



(a) (b)

Figure 15. Measured two-dimensional inertial force.

5. Summary and conclusions

- A 2-DOF linear oscillatory actuator having two lightweight movers with surface permanent magnets was developed for the 2-DOF inertial mass shaker.
- The analysis results indicated that the static thrust constant, stroke, dynamic inertia force and drive frequency range attained the target values. Furthermore, it was noted that the two movers were driven in an electromagnetically independent manner.
- The measurement results obtained using a prototype confirmed that the inertial force attained the target value at the low drive frequency range; however, at a high drive frequency range, the ratio of the measured value to the target value was 78–90%. In addition, undesired harmonics were included at low drive frequencies. Also, it was observed that movers could be driven in a mechanically and electromagnetically independent manner, and the actuator could successfully generate the inertial force in a certain direction.
- The measurement results agreed qualitatively with the analysis results, and the error was likely caused by assembling error and friction and mechanical vibration in the bearings. In the future, we shall consider a more robust design and reselection of bearings.

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