Oscillatory actuators (OAs) are used in various fields, such as industrial equipment and home appliances. For example, they are applied in active vibration isolation tables, vibration test devices, and haptic interfaces. They have a multiple-degree-of-freedom (DOF) mechanism with short-stroke. Such conventional mechanisms consist of some actuators and links, therefore, the vibration center is shifted and the size and weight increase. To solve these problems, various types of multiple-DOF OAs have been developed. However, a five-DOF OA has not been proposed. To further realize the functionality by increasing the DOF, we propose a five-DOF OA. Its basic structure and operating principle are described. The thrust and torque characteristics are investigated by a magnetic field analysis using a three-dimensional finite element method. The analysis results indicate that the proposed actuator can drive five-DOF without interference between other axes.

Keywords: oscillatory actuator, multiple-degree-of-freedom actuator, short stroke actuator, finite element method

1. Introduction

Oscillatory actuators (OAs) have some advantages: small size, simple structure, high responsiveness, and so on. They are applied in various fields such as industrial equipment and home appliances. For example, OAs are used in active vibration isolation tables, vibration test devices, and haptic interfaces, and they have a multiple-degree-of-freedom (DOF) mechanism with short-stroke\(^{(1)-(4)}\). These conventional mechanisms consist of some actuators and links, therefore, the vibration center is shifted and the size and weight increase.

To solve these problems, various types of multiple-DOF OAs are proposed and developed\(^{(5)-(9)}\). The multiple-DOF OA can generate multiple-DOF motion only one device. Therefore, the links are not required in the multiple-DOF mechanism. This feature contributes to downsize and simplify the structure. The two-DOF OA can drive two-DOF with only two-coils and two-phase\(^{(6)}\), it has a flat structure and was designed for a haptic interface. The three-DOF resonance actuator can drive three-DOF with four-coils and four-phase\(^{(7)-(8)}\), it has an axial gap structure. The three-DOF OA can drive three-DOF with three-coils and three-phase\(^{(9)}\), it has a cubic shape. However, a five-DOF OA has not been proposed.

To realize further functionality by an increase of DOF, we propose a novel OA that can drive five-DOF with five-phase. This paper describes the novel magnetic structure and operating principle of the five-DOF OA. The thrust and torque characteristics are clarified by a magnetic field analysis using a three-dimensional finite element method (3-D FEM). The analysis results show that the proposed actuator can drive five-axes without thrust and torque interference.
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Stator Mover
PMs
Back yoke
Whole view

Fig. 2. XYZαβ model of the five-degree-of-freedom oscillatory actuator

(a) Stator (b) Mover

Fig. 3. Arrangement of the magnetic poles, PMs, and coils

plane in the cube (see Fig. 3(b)). The gap between mover and stator is supported by eight coil springs (see Figs. 1 and 2). This arrangement is adopted to achieve same stiffness in each direction.

2.2 Operating Principle

Based on the basic structure and PM and coil arrangement, the actuator can generate thrust and torque by exciting the coils. The operating principle of the XYαβγ model and XYZαβ model are shown in Figs. 4 and 5. From this operating principle and coil arrangement, the actuator can be driven by five-phase. It can be composed that the coils are wound on only one magnetic pole. However, this coil arrangement requires eight-phase to drive five-DOF, or, a large number of coils are needed. On the other hand, the proposed coil and PM arrangement achieves five-DOF motion at least ten-coil. The exciting coil pattern of the one-DOF and five-DOF drives are listed in Tables 1 and 2. In XYαβγ model, the coils 4 and 12, 1 and 9, 3 and 11, 2 and 10, 5-8, are series connected, respectively. In XYZαβ model, the coils 5-8, 3 and 11, 2 and 4, 1 and 9, 10 and 12 are series connected, respectively. Moreover, the currents are applied by five H-bridge circuit.

3. Thrust and Torque Characteristics Analysis

This chapter describes the thrust and torque characteristics. The specifications of the evaluated model for verifying the basic performance are presented. The analysis conditions of the 3-D FEM are shown. The analysis results show that the proposed actuator can drive five-DOF without interference between other axes.

3.1 Evaluated Model and Analysis Conditions

The evaluated model is designed to verify the basic performance. The design parameters of the XYαβγ and XYZαβ model are shown in Figs. 6 and 7, and their values are listed in Table 3. The number of turns of coils is 50 turns. The space factor is about 60%.

Table 1. Coil excitation pattern of one-DOF drive

| Axis | XYαβγ | XYZαβ |
|------|-------|-------|
| X    | 2, 4, 5, 6 | 4, 5, 8, 12 |
| Y    | 7, 8, 10, 12 | 2, 6, 7, 10 |
| Z    | 1, 3, 5, 6 | 1, 5, 6, 9 |
| Thrust | 7, 8, 9, 11 | 3, 7, 8, 11 |
| Torque | 1, 2, 3, 4 | 9, 10, 11, 12 |

Table 2. Coil excitation pattern of five-DOF drive

| Axis | XYαβγ | XYZαβ |
|------|-------|-------|
| X    | 4, 12 | 5, 8 (6, 7) |
| Thrust | 1, 9 | 3, 11 |
| Z    | 3, 4 |
| Torque | 2, 10 | 10, 12 |
| Z    | 5, 7 (6, 8) |
The T-Ω method was employed for the magnetic field analysis\(^{(10)}\). A software (MagNet, Infolytica corp.) was used for the analysis. The 3-D mesh model without the air region is shown in Fig. 8. The analysis conditions are listed in Table 4. The yokes are made of SUY. The residual magnetic flux density of the PM is 1.3 T (N42H), and the coercive force is \(1.0 \times 10^6\) A/m. The current density is 20 A/mm\(^2\) to evaluate the maximum thrust and torque.

3.2 Analysis Results of the XY\(\alpha\beta\gamma\) Model The calculated magnetic flux densities are shown in Fig. 9 when the coils are not excited. It is clarified that the magnetic flux density distribution of the XY\(\alpha\beta\gamma\) model is symmetric.

The analysis results of the detent force, cogging torque, thrust, and torque characteristics are shown in Figs. 10–14, when the coils are excited to drive each axes.

3.2.1 Thrust Characteristics Figures 10 and 11 show the results when the coils are excited to move in the X and Y-axis, respectively. The mover is forcibly translated in the X and Y-axis. The detent force and thrust are generated in only driving axes. The cogging torque and exciting torque are not generated.

3.2.2 Torque Characteristics Figures 12–14 show the results when the coils are excited to rotate in the X, Y, and Z-axis. The detent force and thrust are not generated. The cogging torque and exciting torque are generated in only the driving axis.

3.3 Analysis Results of the XYZ\(\alpha\beta\) Model The calculated magnetic flux densities are shown in Fig. 15, when the coils are not excited. It is found that the magnetic flux density distribution of the XYZ\(\alpha\beta\) model is symmetric.

The analysis results of the detent force, cogging torque, thrust, and torque characteristics are shown in Figs. 16–20, when the coils are excited to drive each axes.

3.3.1 Thrust Characteristics Figures 16–18 show the results when the coils are excited to move in the X, Y, and Z-axis, respectively. The mover is forcibly translated in the X, Y, and Z-axis. The detent force and thrust are generated in only the driving axis.

3.3.2 Torque Characteristics Figures 19–20 show the results when the coils are excited to rotate in the X, Y, and Z-axis. The detent force and thrust are generated in only the driving axis.
the X, Y, and Z-axis. The detent force and thrust are generated in only driving axes. The cogging torque and exciting torque are not generated.

3.3.2 Torque Characteristics Figures 19 and 20 show the results when the coils are excited to rotate in the X and Y-axis. The detent force and thrust are not generated. The cogging torque and exciting torque are generated in only the driving axis.

3.4 Discussion The detent force and cogging torque characteristics have a positive slope attendant on the rotational and translational motion. Therefore, the mechanical spring is needed in the supporting mechanism to stable at the origin point.

From the analysis results of the thrust and torque characteristics, it is found that the proposed actuator can generate a five-DOF motion without interference between other axes. Moreover, their thrust and torque characteristics are flat in the operating range. The small thrust variation occurs due to the changing magnetic reluctance. The air gap on one side is shortened, and that of the other side is expanded, during translational motion. In this situation, the magnetic reluctance is changed and the thrust characteristics have non-
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Fig. 15. Magnetic flux density distribution of the XYZαβ model

Fig. 16. Analysis results of the XYZαβ model when the coils are excited to move in the X-axis

Fig. 17. Analysis results of the XYZαβ model when the coils are excited to move in the Y-axis

Fig. 18. Analysis results of the XYZαβ model when the coils are excited to move in the Z-axis

linearity. The magnetic saturation is occurred on one side, when the mover is at \(-0.5\) mm, as shown in Fig. 21. On the other hand, the air gap length is not changed during rotation. Therefore, the torque characteristics have no variation, and there is no saturation (see Fig. 21).

For applying to an oscillatory device, the design of the frequency characteristics is important such as a resonant frequency set. In the proposed actuator, the resonant frequency can be adjusted by changing the stiffness of the magnetic spring.

4. Frequency Characteristics

The frequency response is analyzed in this chapter. The mathematical model of the proposed actuator is presented. The frequency characteristics in the current input are calculated.

4.1 Mathematical Model The output force of the actuator is defined as follows:

\[ F_i = k_b I_i + k_{di} p_i \]

where \( F_i \) is the output force, \( k_b \) is the thrust constant, \( I_i \) is the current, \( k_{di} \) is the detent force constant as the stiffness of the magnetic spring, \( p_i \) is the position, \( i \) is each axis. The equation of motion in the linear motion is defined as follows:

\[ m \frac{d^2 p_i}{dt^2} + c_i \frac{dp_i}{dt} + k_{eiti} p_i = F_i \]

where \( m \) is the weight of the mover, \( c_i \) is the viscous friction coefficient in the linear motion, and \( k_{eiti} \) is the spring constant of a mechanical spring in the linear motion. The transfer function, where the input is current and the output is the displacement, is defined as follows:
where $P_{li}$ is the transfer function in the linear motion. The output torque is defined as follows:

$$T_i = k_{ti} I_i + k_{ci} \theta_i$$ \hspace{1cm} (4)

where $T_i$ is the output torque, $k_{ti}$ is the torque constant, $k_{ci}$ is the cogging torque constant as the stiffness of the magnetic spring, $\theta_i$ is the angle, $i$ is each axis. The equation of motion in the rotational motion is defined as follows:

$$T_i = J_i \frac{d^2 \theta_i}{dt^2} + c_{ri} \frac{d \theta_i}{dt} + k_{ser} \theta_i$$ \hspace{1cm} (5)

where $m$ is the weight of the mover, $c_{ri}$ is the viscous friction coefficient in the rotational motion, and $k_{ser}$ is the spring constant of the mechanical spring in the rotational motion. The transfer function, where the input is current and the output is the angle, is defined as follows:

$$P_{ri}(s) = \frac{K_{ri}}{J_i s^2 + c_{ri} s + (k_{ser} - k_{ci})}$$ \hspace{1cm} (6)

where $P_{ri}$ is the transfer function in the rotational motion. The parameter values are listed in the Table 5. The parameters were obtained by the results of the 3-D FEM. The detent...
force and cogging torque constants were calculated as a linear approximation of detent forces and cogging torques. The viscous friction coefficients were used one example value as an experience value.

4.2 Calculated Results The frequency characteristics of the two models are shown in Figs. 22 and 23. As an example, the stiffness of the mechanical spring is decided so that the resonance frequency is 50 Hz. From the calculated results, it is confirmed that the resonance frequency is 50 Hz.

5. Conclusion This paper proposed the five-DOF OAs: the XYαβγ and XYZαβ model. The effectiveness of the proposed actuator was verified by the magnetic field analysis using 3-D FEM and frequency characteristics analysis. The analysis results showed that the actuator can generate thrust and torque without interference between other axes. In future work, the analysis validity and dynamic performance are investigated using a prototype.

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