Design of Two-Degree-of-Freedom Electromagnetic Actuator using PMSM and LSM

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This paper presents the design and analysis of two-degree-of-freedom actuator that can move in rotary and linear direction. The proposed actuator is moved in principles of permanent magnet synchronous motor and linear synchronous motor. The structure of the actuator is robust to use the ring magnets that magnetized in axial direction. Moreover, the stator of the actuator has the salient pole in axial direction for improvement of thrust density. Characteristics of the actuator are analyzed by three-dimensional finite element method. As a result, the actuator is obtained characteristics that the average torque is 61.8 mNm in rotary motion and the average thrust is 9.00 N in linear motion.

Keywords: Two-degree-of-freedom, Permanent magnet synchronous motor, Linear synchronous motor, Finite element method.

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1. Introduction

Recently, the drive mechanism is complex configurations as the electronic component mounting apparatus and the machine tool are high performance. The head portion of those is the drive mechanism with two-degree-of-freedom of rotary and linear motion. Generally, it is realized the combination of 2 motors and mechanical elements. Mechanical elements to convert linear motion to rotation are the ball screw, etc. However, the drive mechanism is huge, heavy and in need of maintenance by abrasion. Therefore, two-degree-of-freedom actuator of rotary and linear motion is required high quality and the drive by electromagnetic force [1, 2].

Authors focused on two-degree-of-freedom actuator [3] using permanent magnet synchronous motor (PMSM) and linear synchronous motor (LSM) [4]. The mover of the actuator in reference [5, 6] has the segment magnets, such as Fig. 1 (a). The actuator is moved in principles of PMSM and LSM by arranging the magnetic pole in radial direction and axial direction. However, it is difficult to adhere the magnets on given position. It needs method to prevent the scatter of the magnets. In addition, the actuator is a shaft motor without the salient pole in axial direction. Thus, the actuator is inferior to the actuator with one from the standpoint of thrust density.

In this paper, two-degree-of-freedom actuator is proposed by using the ring magnets that magnetized in axial direction, such as Fig. 1 (b) for the structure of simplicity and robustness. The stator of the actuator has salient pole in axial direction for improvement of thrust density. It is described the operating principle of the actuator and evaluated characteristics by electromagnetic field analysis of three-dimensional finite element method (3D-FEM). Moreover, the high-efficient actuator is realized by considering the number of poles in axial direction.

2. Electromagnetic Field Analysis by 3D-FEM

The fundamental equation for electromagnetic field analysis that considers permanent magnet is represented by the following equation [7, 8].

\[ \text{rot} (\nu \text{rot} A) = J_0 - \sigma \frac{\partial A}{\partial t} + \nu_0 \text{rot} M \]  \hspace{1cm} (1)

Where, \( \nu \) is magnetic resistivity, \( A \) is magnetic vector potential, \( J_0 \) is forced current density, \( \sigma \) is electric conductivity, \( \nu_0 \) is magnetic resistivity in vacuum, \( M \) is residual magnetic flux density of permanent magnet.

3. Proposed Structure and Operating Principle

3.1 Basic Structure

Basic structure and specification of the proposed actuator are shown in Fig. 2 and Table 1. The stator is composed of the back yoke, the salient pole stator, the coil for rotary motion and the coil for linear motion. The salient pole stator has 6 salient poles in radial direction and 7 salient poles in axial direction. The salient pole...
stator is constituted 6 units, and 1 unit of the salient pole stator is defined as 7 salient poles in axial direction, such as Fig. 3 (a). The coil for rotary motion is wound to each 1 unit in advance. 1 unit is arranged at intervals of 60 degrees in radial direction, and 6 units in total are rounded in a circle. The coil for linear motion of toroidal is arranged between salient poles in axial direction, respectively. The salient pole stator with the coil for rotary and linear motion is joined the back yoke [9]. Thus, the stator is composed of 6 slots in radial and axial direction. The mover is composed of the mover yoke, such as Fig. 3 (b), the permanent magnet (residual magnetic flux density: 1.32 T) and the non-magnetic shaft. The mover yoke of N-pole and S-pole in Fig. 3 (b) are arranged apart 45 degrees in rotary direction. Besides, the mover is composed by inserting alternately the ring magnets that magnetized in axial direction between the mover yoke of N-pole and S-pole to the non-magnetic shaft. Therefore, the mover yoke are magnetized NS-pole in radial and axial direction.

3.2 Operating principle of Rotary Motion

The view from the positive direction in z-axis of the proposed actuator is shown in Fig. 4. The mover has 8 salient poles in Fig. 4. As described in section 3.1, the mover yoke are magnetized NS-pole because of the ring magnets. Therefore, the proposed actuator is 8 poles 6 slots PMSM in rotary direction. The coil for rotary motion is arranged U_R, V_R, and W_R-phase in 6 slots. Rotating magnetic field is generated by three-phase alternating current, and the mover moves in rotary direction.

Table 1 Specification of the proposed actuator

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of the stator</td>
<td>26mm</td>
</tr>
<tr>
<td>Diameter of the mover</td>
<td>12mm</td>
</tr>
<tr>
<td>Diameter of the non-magnetic shaft</td>
<td>4.0mm</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.2mm</td>
</tr>
<tr>
<td>Number of slots in radial direction</td>
<td>6</td>
</tr>
<tr>
<td>Number of poles in radial direction</td>
<td>8</td>
</tr>
<tr>
<td>Number of turns of coil for rotary motion</td>
<td>50turn</td>
</tr>
<tr>
<td>Length of the stator</td>
<td>45mm</td>
</tr>
<tr>
<td>Length of the mover</td>
<td>99mm</td>
</tr>
<tr>
<td>Slot pitch</td>
<td>7.5mm</td>
</tr>
<tr>
<td>Pole pitch</td>
<td>9.0mm</td>
</tr>
<tr>
<td>Number of slots in axial direction</td>
<td>6</td>
</tr>
<tr>
<td>Number of poles in axial direction</td>
<td>11</td>
</tr>
<tr>
<td>Number of turns of coil for linear motion</td>
<td>55turn</td>
</tr>
<tr>
<td>Magnetic material</td>
<td>M-19</td>
</tr>
<tr>
<td>Residual magnetic flux density</td>
<td>1.32 T</td>
</tr>
</tbody>
</table>

(a) 1 unit of salient pole stator     (b) Mover yoke
Fig. 3. Shape of salient pole stator and mover yoke.

Fig. 2. Basic structure of the proposed actuator.

Fig. 4. View of the positive direction in z-axis.
3.3 Operating Principle of Linear Motion

The cross-sectional view in y-z plane of the proposed actuator is shown in Fig. 5. The parameters in axial direction are represented by the following equation because the proposed actuator is designed as 5 poles 6 slots LSM [10].

\[ L_s = 6\tau_s = 5\tau_p \]  

Where, \( L_s \) is the length of the stator, \( \tau_s \) is the slot pitch, \( \tau_p \) is the pole pitch. In this paper, \( L_s \) is 45 mm, \( \tau_s \) is 7.5 mm and \( \tau_p \) is 9.0 mm. The mover is added to extra 3 poles at top and bottom to consider the movable scope. Therefore, the number of poles in axial direction is 11 poles in total. The coil for linear motion is arranged \( U_l, -U_l, V_l, -V_l, W_l \) and \( -W_l \)-phase in 6 slots (the positive direction is from front to rear). As rotary motion, shifting magnetic field is generated by three-phase alternating current, and the mover moves in axial direction.

4. Characteristics of the Proposed Actuator

The proposed actuator is analyzed by 3D-FEM to evaluate characteristics of rotary and linear motion. Analysis model is surrounding 1/2 model by symmetry. The positive values of magnetic flux density, the torque and the thrust is defined as radially outward, counter clockwise and positive direction in z-axis. The values of exiting current in rotary and linear direction is 2.5 A.

4.1 Magnetic Flux Density Distribution

Magnetic flux density of air gap is generated by the ring magnets that magnetized in axial direction. Magnetic flux density waveforms in rotary direction are shown in Fig. 6. The proposed actuator has the salient poles in radial and axial direction. Therefore, it is difficult to confirm the period of the magnetic pole by one magnetic flux density waveform. In this paper, the period of the magnetic poles is simply confirmed by summing two magnetic flux density waveforms in condition of the reversed polarity, such as Fig. 7. A and B in Fig. 7 is the position in z-axis. The position of A is 19.5 mm, and the position of B is -19.5 mm. The mover yoke of N-pole and S-pole opposes the salient stator similarly in the position of A and B. Thus, A and B are in condition of the reversed polarity. A and B waveforms in Fig. 6 is magnetic flux density waveforms in the position of A and B. A + B waveform represents sum of A and B waveforms. The period of A + B waveform is the same as the period of magnetic pole of the proposed actuator, but the value of magnetic flux density are not same. The period of the waveform is 90 degrees in rotation angle. Therefore, the magnetic pole is 8 poles in rotary direction. The period of magnetic pole in linear direction is confirmed in the same way as the rotary direction. Magnetic flux density waveforms in linear direction are shown in Fig. 8. Position of C and D to confirm the magnetic flux density in linear direction is shown in Fig. 9. C + D waveform represents sum of C and D waveforms. Therefore, the magnetic pole is 5 poles in linear direction.
4.2 Characteristics of torque and thrust

It is shown the characteristics in rotary direction. The cogging torque waveform of the proposed actuator is shown in Fig. 10. By relation of 6 slots and 8 poles, the period of the waveform is 15 degrees in rotation angle, and the peak-to-peak value of the waveform is 1.50 mNm. The torque waveform is shown in Fig. 11. The average value of the torque waveform is 48.5 mNm.

Moreover, it is shown the characteristics in linear direction. The thrust waveform along the current phase is shown in Fig. 12. The waveform is distributed as sine wave. The maximum value of the waveform is 9.71 N as the current phase angle $\beta = 210$ degrees. The detent force waveform without exciting current and the thrust waveform as the current phase angle $\beta = 210$ degrees are shown in Fig. 13. The horizontal axis of Fig. 13 is the position from 0 mm to 18 mm ($2\tau_m = 18$ mm). The peak-to-peak value of the detent force waveform is 6.61 N. The average value of the thrust waveform is 8.94 N.
5. Characteristics of Changing Number of Poles in Axial Direction

5.1 Comparison of 5 Poles Model and 7 Poles Model

To reduce detent force, the number of poles of the actuator is changed from 5 poles to 7 poles in contrast 6 slots. The model that is analyzed in chapter 4 is defined as 5 poles model, and the model that is analyzed in this chapter is defined as 7 poles model. Specification of 7 poles model is shown in Table 2, and in comparison with the Eq. (2), the parameters of 7 poles model represented by the following equation.

\[ L_s = 6\tau_s = 7\tau_p \]  (3)

\( L_s \) is 42 mm, \( \tau_s \) is 7.0 mm and \( \tau_p \) is 6.0 mm. As with the 5 poles model, the mover of 7 poles model is added to extra 3 poles at top and bottom. The comparison of two models is shown in Fig. 14. The length of the stator and the mover of 7 poles model is smaller. By changing number of poles, the length of the stator is changed from 45 mm to 42 mm, and the length of the mover is changed from 99 mm to 78 mm. Moreover, magnetomotive force in analysis condition is reduced in depend on slot in axial direction.

5.2 Characteristics of 7 Poles Model

The 7 poles model is analyzed characteristics in rotary and linear direction. The characteristics in this section are shown along with the 5 poles model.

The cogging torque and the torque waveforms of 7 poles model is shown in Fig. 15 and Fig. 16. By reducing the length of the stator, the cogging torque waveform of 7 poles model is decreased 30% compared with 5 poles model. The peak-to-peak value of the waveform is 1.05 mNm. Moreover, the average value of the torque waveform is 61.8 mNm and increased 27%.

It is shown the characteristics in linear direction. The thrust waveform along the current phase of 7 poles model is shown in Fig. 17. The maximum value of the waveform is 9.13 N as the current phase angle \( \beta = 30 \) degrees. The detent force waveform without exciting current and the thrust waveform as the current phase angle \( \beta = 30 \) degrees are shown in Fig. 18. The horizontal axis in Fig. 18 is the position from 0 mm to 12 mm (\( 2\tau_p = 12 \) mm). The peak-to-peak value of the detent force waveform is 3.73 N. The average value of the thrust waveform is 9.00 N. Although the average value of the thrust waveform is approximately the same value compared with 5 poles model, the peak-to-peak value of detent force waveform is decreased 44%.

Torque and thrust characteristics of 7 poles model is shown in Fig. 19. It is confirmed that the torque and the thrust is approximately proportional to current.
6. Conclusion

In this paper, authors proposed the two-degree-of-freedom actuator using PMSM and LSM to realize the drive mechanism with two-degree-of-freedom of rotary and linear motion. The structure of the actuator is robust to use the ring magnets that magnetized in axial direction. Characteristics of the actuator were analyzed by 3D-FEM. It was confirmed that magnetic flux density of air gap is generated as the structure of the actuator.

The number of poles in axial direction was changed from 5 poles to 7 poles. The diameter and the length of the actuator are 26 mm and 78 mm. The actuator was obtained characteristics that the average value of the torque is 61.8 mNm in rotary motion and the average value of the thrust is 9.00 N in linear motion.

Future work will optimize shape of the mover and the stator because of reducing values of cogging torque and detent force.

References


