Design and Characteristic Analysis of Small-Sized and High Thrust Electromagnetic Actuator on High Temperature Field

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This paper presents the design and characteristic analysis of small-sized and high thrust electromagnetic actuator in the high temperature field. The proposed actuator is used for application control of hotmelt. Hotmelt is thermoplastic resin and solid at room temperature, and it is used as adhesives. Therefore, the actuator is required small-sized and high thrust in the high temperature field. The actuator is analyzed by 3D-FEM. As a result, the actuator obtains high thrust over required thrust 132 N. In addition, modifying the coil shapes enables to suppress of temperature rise.

Keywords: Electromagnetic actuator, Coupled analysis of temperature and electromagnetic field, Finite element method

1. Introduction

Nowadays, pneumatic actuator is used for hotmelt applicator. The pneumatic actuator is a simple structure and can accumulate energy in the tank, therefore it is high thrust. On the other hand, the pneumatic actuator has problems that the cylinder packing wears due to long term use and large equipment such as air compressor and pipe for producing compressed air is required. On the contrary, the electromagnetic actuator can be driven by the power supply[1,2], thus the equipment can be minimized. Furthermore, it is operated by using suction and repulsion of permanent magnet and electromagnet, therefore it has good responsiveness[3]. However, the whole actuator model becomes hot by heating and melting the hotmelt in the applicator. The magnetic characteristic of the permanent magnet change depending on the temperature. Therefore, when the permanent magnet becomes hot due to the ambient temperature, the thrust and the responsiveness are decreased[4].

In this paper, it is described the operating principle of the proposed actuator and evaluated the characteristics by coupled analysis of temperature and electromagnetic field with three-dimensional finite element method (3D-FEM)[5,6]. Moreover, it is considered the suppression of temperature rise of the actuator by modifying the coil shape.

2. Basic structure of proposed actuator and operating principle

2.1 Basic structure of proposed actuator

The basic model of proposed actuator consists mainly a stator and a mover, a plunger needle, a cover. Fig. 1 shows the structure of the stator of proposed actuator, and Fig. 2 shows the structure of the mover of proposed actuator, and Fig. 3 shows the basic structure of proposed actuator. The electromagnetic actuator has size limit because it is supposed to replace pneumatic actuator used at factories. Therefore, the proposed actuator is optimized and it can use limited space effectively. The stator and the mover are provided with holes for passing the plunger needle in the y-axis direction. In this paper, the plunger needle and the cover are not considered.

The stator is composed of the stator cores and coil yokes, coil bobbins, coils. The stator cores are two patterns; upper core, bottom core. There cores are arranged in the chain pattern. Coil yokes are arranged between the stator upper cores and the stator bottom cores. Coil bobbins are arranged outside of coil yokes and coils are wound on coil bobbins. The mover is composed of the mover cores and the permanent magnet. The permanent magnet is arranged between two mover cores.

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Fig. 1 Structure of the stator of proposed actuator

Fig. 2 Structure of the mover of proposed actuator
2.2 Operating principle

Fig. 4 shows the magnetic flux flow of proposed actuator. The mover cores are magnetized by the magnetic field generated by the permanent magnet. The stator cores are magnetized by the magnetic field generated by the electromagnet. Between magnetized mover cores and stator cores, electromagnetic forces are generated. Thus, an upward thrust works to the mover. On the other hand, the magnetic poles of the stators are changed by changing the direction of flowing current. Thus, a downward thrust works to the mover.

2.3 Extension to two stage model

The feature of the proposed actuator is where high thrust can be obtained by stacking the basic model shown in Fig. 3 in the axial direction or arranging them in the radial direction. Two stage model is stacked with two basic models in the y-axis direction. Fig. 5 shows the structure of the stator of the two stage model, and Fig. 6 shows the structure of the mover of the two stage model, and Fig. 7 shows the structure of the whole two stage model.
2.4 Range of motion

Fig. 9 shows the top view of the proposed actuator. The range of the motion for the mover is 0.3 mm. The mover goes and returns from the descending stroke end to the ascending stroke end. When the mover is at the descending stroke end, the gap between the mover cores and the descending side stator cores is 0.2 mm. When the mover is at the ascending stroke end, the gap between the mover cores and the ascending side stator cores is 0.2 mm. In order to consider the motion of the mover, the equation of motion is set, as shown in (1). Where, parameter $F$ means the electromagnetic force and $M$ means the mass of the mover, $\gamma$ means damper component, $K$ means the spring component. In this paper, the actuator is a no-load condition. Thus $\gamma$ and $K$ is 0, and $M$ is calculated from the density of the material.

$$F = M \frac{d^2y}{dt^2} + \gamma \frac{dy}{dt} + K \tag{1}$$

When the mover is at the descending stroke end, the adhesive discharge port provided in the lower part of the actuator opens and the adhesive is applied. When the mover is at the ascending stroke end, the adhesive discharge port closes and the adhesive is cut off. Therefore, the actuator is required high thrust in the $y$-axis positive direction particularly, for realization complex application methods. The actuator is required high thrust over 132 N.

3. Electromagnetic field analysis

3.1 Analysis conditions

Table 1 shows the specification of the two stage model\cite{7,8}. The rise time of the current is 0.125 ms and the frequency is 500 Hz.

3.2 Analysis result

The thrust and the responsiveness of the two stage model are analyzed. At the start of analysis, the mover is at the descending stroke end. The positive $y$-axis direction is assumed to be positive thrust, and Fig. 10 shows the thrust waveform and current characteristics of the two stage model.

| Table 1 Specification of the two stage model |
|---------------------------------------------|
| Element number                              | 636439 |
| Number of nodes                             | 108505 |
| Gap length [mm]                             | 0.2-0.5 |
| Number of coil turn                         | 526    |
| Material of magnet                          | NEOMAX-35AH |
| Residual magnetic flux density [T]           | 1.2    |
| Material of core                            | FMCM-HB1 |
| Saturation magnetic flux density [T]         | 1.8    |
When the mover is at the descending stroke end, the mover core is closer to the descending side stator core than the ascending side stator core. Because of this, the suction force -20 N by the permanent magnet is generated at the start of analysis. After passing current, the actuator generates the high thrust by the suction and repulsion forces by the permanent magnet and electromagnet. Moreover, as the mover core approaches the ascending side stator core and the gap length becomes shorter, the actuator obtains larger thrust. When the mover reaches the ascending stroke end, the thrust becomes constant at 169 N over the required thrust 132 N. When the rectangular current becomes 0 A, the suction force 20 N by the permanent magnet is generated since the mover is at the ascending stroke end. The thrust varies in the same way, depending on the direction of flowing current.

Fig. 11 shows the stroke and current characteristics of the two stage model. After passing current, the mover starts to ascend from the descending stroke end, and reaches the ascending stroke end in about 0.74 ms. The mover starts to descend from the ascending stroke end by changing the direction of flowing current, and reaches the descending stroke end in about 1.74ms.

Fig. 12 shows the magnetic flux density distribution of the two stage model in 0.875 ms. In Fig. 12, the mover is at the ascending stroke end, and the current value is 1 A. The coils and coil bobbins are not displayed for the convenience. The magnetic flux density of the whole model doesn’t exceed 1.8 T. Therefore, it is not flux saturated.

Fig. 13 shows the loss of the stator and the mover with the permanent magnet, and Fig. 14 shows the breakdown of the iron loss on the two stage model[9]. The copper loss of the coils and the iron loss of the coil yoke are large. The number of coil turns is 526, and it has a high resistance. Therefore, the copper loss is large. The coil yoke has a small magnetic path cross-sectional area, and the flux density is large on it. Therefore, the iron loss of the coil yoke is large.
4. Coupled analysis of temperature and electromagnetic field

4.1 Analysis condition

Table 2 shows the analysis parameters of coupled analysis of temperature and electromagnetic field[10]. The initial temperature of the whole model including outside air is 20 degrees. The air assumes natural convection, and the heat transfer coefficient is 10 in order to express the heat transfer between the model and the outside air.

| Parameter                        | Value |
|----------------------------------|-------|
| Initial temperature [degree C]   | 20    |
| Heat transfer coefficient [W/m²/K]| 10    |

4.2 Analysis result

Fig. 15 shows the temperature distribution on the two stage model in 20 minutes after the start of operation of the actuator. The average temperatures of the coil and the coil yoke, the permanent magnet are 153.5 degrees and 150.6 degrees, 118.5 degrees. In Fig. 15 indicates heat is transferred to the surrounding parts around the coil.

4.3 Modifying coil shape and suppression of temperature rise

Then, for the purpose of the suppression of temperature rise, it is considered that the actuator model is modified. The actuator has a large copper loss, therefore the model changes the two division model without changing the number of coil turns, and the three division model also analyze similarly. Fig. 16 (a) and (b) show the structures of two division model and three division model. The coil is divided into two in the two division model. Similarly, the coil is divided into three in the three division model. Fig. 17 and Fig. 18 show the temperature distributions of each model in 20 minutes after the start of operation. According to Fig. 17, the average temperatures of the coil and the coil yoke, the permanent magnet of the two division model are 135.2 degrees and 133.8 degrees, 107.8 degrees. It is able to radiate heat from the coil. Therefore, the temperature rise can be reduced.

On the other hand, according to Fig.18, the average temperatures of the coil and the coil yoke, the permanent magnet of the three division model are 149.8 degrees and 147.7 degrees, 116.5 degrees. This model didn’t radiate heat than the two division model. This reason is because the divided coil intervals are not long enough to radiate heat from the coil and the coil yoke to the air.

The two division model can be radiated heat. Therefore, we compared the characteristic of the non-division model and the two division model. Fig. 19 shows the relationship of temperature of the permanent magnet and thrust. According to Fig. 19, the two division model generates higher thrust and lower temperature of the permanent magnet than the non-division model. Moreover, the two division model generates 157 N over required thrust 132 N in 20 minutes. Therefore, it can operate normally even if the permanent magnet becomes high temperature.
5. Conclusion

In this paper, authors designed the basic model and extend it to the two stage model for the hotmelt applicator and described the operating principle. The feature of the two stage model is where high thrust can be obtained by stacking the basic model in the axial direction or arranging them in the radial direction. The characteristics of the actuator were analyzed with 3D-FEM, and the two stage model realized high thrust over required thrust 132 N. In addition, changing the coil shapes realized to suppression of temperature rise.

Future work will design and analyze with the full model of the actuator including plunger needle and cover. Furthermore, it will optimize for the purpose of the reducing loss.

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