High Torque Density Permanent Magnet Brake

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Abstract. As the braking device of the aircraft electromechanical actuation system, the brake is a vital link in the aircraft attitude change or function adjustment. Among them, the permanent magnet brake has attracted extensive attention in the field of aerospace technology because of its advantages of low energy consumption and high reliability. At present, the domestic permanent magnet brake is heavy and the braking torque density is generally low, which limits its further development in the field of aerospace. In order to improve the braking torque density of permanent magnet brake, this paper proposes a research method of high torque density permanent magnet brake is proposed. By establishing the magnetic circuit structure of the permanent magnet brake, the relationship between the external characteristics of the permanent magnet brake and the design parameters is determined, and then the performance parameters of the permanent magnet brake are simulated and verified by using the finite element simulation software. Finally, through the physical test, the results show that this method can effectively improve the braking torque density.

1. Introduction

With the rapid development of aviation science, as a braking device with simple structure and wide versatility, the brake plays a more and more important role in military and civil fields, especially in the fields of aerospace, military vehicle and ship braking. At present, the brake mainly includes mechanical brake and electromagnetic brake. The mechanical brake is mainly used in the automotive field [1], while the spring electromagnetic brake is widely used in aircraft electric actuator and aircraft electromechanical actuator (EMA) because it does not need to be powered on for a long time to maintain the braking state [2]. It has a wide application prospect. However, the spring electromagnetic brake completely relies on the elastic force of the spring on the armature to realize friction braking, which leads to the problems of large volume, heavy weight and low reliability. These shortcomings greatly limit its further application in the field of aerospace.

With the development of rare earth permanent magnet materials such as Nd-Fe-B, permanent magnet brakes are gradually applied in the field of aviation technology [3]. The permanent magnet brake relies on the attraction of the permanent magnet to the armature to adsorb the armature to the friction surface, and then produce friction torque to realize braking; After the current is applied to the coil, the magnetic field of the permanent magnet is offset, and the armature is separated from the friction surface under the action of the spring to release [4]. Because the permanent magnet brake does not need to consider the requirements of spring performance, the braking state can be realized only by the suction of the permanent magnet to the armature. Therefore, the permanent magnet brake not only has the characteristics of small volume, light weight and low energy consumption, but also has the advantages
of simple structure, stable suction and high reliability [5], which is very suitable for the application in the field of aerospace. However, when the braking torque of current permanent magnet brake products is 3N.M, the braking torque density is low, about 8.6N.M/kg. In addition, the permanent magnet brake has high requirements for the overall performance of permanent magnet materials and is greatly affected by temperature, which undoubtedly limits the application of permanent magnet brake.

In this paper, the problem of low braking torque density of permanent magnet brake is studied. The main contents include: the second section establishes the magnetic circuit structure of high torque density permanent magnet brake, and determines the relationship between the external characteristics of permanent magnet brake and important design parameters. In Section 3, the suction force of permanent magnet brake is simulated and verified by simulation software. In Section 4, the weight and braking torque density of permanent magnet brake are given and the physical test verifies the effectiveness of the method.

2. Research method of high torque density permanent magnet brake

2.1. Magnetic circuit structure of permanent magnet brake

Permanent magnet brake includes rotor disc, outer support, armature, spring, inner support, permanent magnet and coil. The magnetic circuit structure of permanent magnet brake in braking state and release state is shown in Figure 1.

![Fig 1. Magnetic circuit structure of permanent magnet brake](image)

The red line represents the magnetic path of the permanent magnet and the yellow line represents the magnetic path after the coil is energized. The working principle of permanent magnet brake is: under the action of permanent magnet suction, the armature overcomes the elastic force of spring and contacts with stator to produce braking torque. At this time, the force on the armature is:

\[ F = F_1 - F_2 \]  

(1)

\( F_1 \) denotes the suction force of the permanent magnet and \( F_2 \) denotes the spring force. In the release state, the armature is subjected to the electromagnetic force generated by the magnetic field generated by the coil and the magnetic field of the permanent magnet, as well as the tension of the spring. At this time, the spring tension is greater than the permanent magnetic force. Therefore, the armature is separated from the guide magnet to realize the release state. When the \( F_3 \) denotes the electromagnetic force, the force on the armature is:

\[ F = F_2 - F_3 \]  

(2)

2.2. Relationship between external characteristics and design parameters

When the size of the spring is given, the air gap spacing is determined to be 0.02mm-0.4mm, the restoring force \( F \) of the spring can be obtained. Since the braking torque is generated by the friction of
two friction rings composed of stator and armature, after giving the inner and outer diameter of the ring, according to the ring friction formula:

$$T=\frac{2}{3}\mu P\pi[(R_1^3-R_2^3)+(R_3^3-R_4^3)]$$

$$P=\frac{F}{S}$$

(3)

$\mu$ denotes the friction coefficient and $P$ denotes the pressure of the friction pair. According to Maxwell's suction formula, the relationship between suction $F$ and magnetic induction intensity $B$ in magnetic circuit is:

$$F=\frac{B^2S}{2\mu_0}$$

(4)

$S$ denotes the air gap area, $\mu_0$ denotes vacuum permeability: $\mu_0=4\pi\times10^{-7}$. Therefore, the relationship between braking torque $T$ and magnetic induction intensity $B$ can be obtained.

When the braking torque of permanent magnet brake is required to be 3N.M, the required suction force can be calculated as 500N according to the friction torque formula. Considering that high temperature will reduce the magnetic properties of permanent magnet, the given suction force is 600N. By formula:

$$\Phi_{\text{air gap}}=BS$$

$$R=\frac{l}{\mu_0 S}$$

(5)

The air gap flux, air gap reluctance, magnetic circuit reluctance and leakage reluctance can be obtained. The magnetoresistance of the permanent magnet can be calculated by setting the thickness and area of the permanent magnet first. By formula:

$$\Phi_{\text{air gap}}(R_{\text{air gap}}+R_{\text{magnetic circuit}}) = \Phi_{\text{Magnetic leakage}} R_{\text{Magnetic leakage}}$$

(6)

The leakage flux and main flux can be obtained. It can be obtained from Kirchhoff's second law of magnetic circuit:

$$H_{\text{Permanent magnet}} = \Phi_{\text{main flux}} R_{\text{ Permanent magnet}} + \Phi_{\text{air gap}} (R_{\text{air gap}} + R_{\text{magnetic circuit}})$$

(7)

The size of the final permanent magnet can be determined. In the released state, the magnetic flux generated by the coil and the magnetic flux of the permanent magnet cancel each other. The suction in the given release state is 0.1N. When setting the number of ampere turns of the coil, according to the formula:

$$\Phi_{\text{air gap}} R_{\text{air gap}} + NI = \Phi_{\text{Magnetic leakage}} R_{\text{Magnetic leakage}}$$

$$\Phi_{\text{main flux}} = \Phi_{\text{air gap}} + \Phi_{\text{Magnetic leakage}}$$

$$H_{\text{Permanent magnet}} - NI = \Phi_{\text{Permanent magnet}} R_{\text{ Permanent magnet}} + \Phi_{\text{air gap}} R_{\text{ air gap}}$$

(8)

The final coil ampere turns can be obtained. The number of turns and current of the coil can be determined by the cross-sectional area and slot fullness of the coil.

3. Electromagnetic simulation and thermal simulation

3.1. Simulation verification of braking process

In the breaking state, the armature moves from 0.4mm to 0.02mm. The magnetic field distribution obtained by simulation is shown in Fig 2.
Fig 3 shows the change of permanent magnet suction with armature spacing. It can be seen that the suction increases rapidly with the decrease of spacing. When the spacing is 0.02mm, the suction of permanent magnet reaches 600N. After deducting the spring tension, the actual friction pair pressure of permanent magnet brake is 532N, which can meet the braking torque requirement of 3N.M.

3.2. Simulation verification of release process

In the released state, the given voltage is 25V, which is determined by the resistance formula:

\[ R = \frac{\rho L}{S} \]  

(9)

The \( \rho \) denotes the resistivity of copper, \( L \) denotes the coil length, \( S \) denotes the coil cross-sectional area, therefore the resistance and the current at 20 °C can be calculated. The magnetic field in the release process is simulated as shown in Fig 4.

Figure 5 shows the change of electromagnetic suction when the armature is released. It can be seen that under the condition of opening voltage of 25V, the coil electromagnetic force offsets the permanent
magnetic field, and the suction is within 0.1N. Therefore, under the action of spring force, the armature can return to the release position.

3.3. Temperature effect analysis

In high temperature environment, the coil resistance will increase, the corresponding current will decrease, and the electromagnetic suction will change significantly. By formula:

\[ R_T = [1 + 0.0039(x(T-20))] \times R_{20} \]  

(10)

The resistance and current at -40 °C, 80 °C and 150 °C can be calculated. Fig 6 shows the relationship between electromagnetic suction and coil voltage at -40 °C, 20 °C, 80 °C and 150 °C. With the increase of temperature, the opening voltage range gradually moves in the direction of voltage increase.

In low temperature environment, due to the decrease of coil resistance, the input current increases after the opening voltage is applied. Therefore, NTC resistance is added to the controller. Figure 7 shows the relationship between electromagnetic suction and coil voltage after adding NTC. Since NTC resistance is added at -40 °C low temperature, the equivalent coil resistance is increased, and the low temperature opening voltage range changes significantly.

Fig 5. Variation of electromagnetic suction with armature spacing

Fig 6. Relationship between electromagnetic suction and coil voltage

Fig 7. Relationship between electromagnetic suction and coil voltage after adding NTC
Therefore, the opening voltage is set to 28V. It can be seen from the figure that when the braking torque of permanent magnet brake is 3N.M, the weight is 0.233kg, and the braking torque density is 12.87N.M/kg, which is higher than the existing products. It proves the effectiveness of the design method of high torque density permanent magnet brake.

Fig 8. Physical test diagram of permanent magnet brake

4. Conclusion
This paper presents a research method of high torque density permanent magnet brake. By establishing the magnetic circuit structure of the permanent magnet brake, the relationship between the external characteristics of the permanent magnet brake and the design parameters is determined, and then the performance parameters of the permanent magnet brake are simulated and verified by using the finite element simulation software. The physical test proves the effectiveness of the research method, and has important practical significance for the research of permanent magnet brake.

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