Armature Optimization Design Based on Orthogonal Test

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Abstract. Armature is the core component of electromagnetic launcher. It not only plays the role of constituting current loop, but also provides launching power for projectile. Therefore, armature optimization is a key step to improve the comprehensive performance of six-pole orbital electromagnetic launcher. In this paper, the finite element simulation software Ansoft Maxwell is used to simulate and analyze the armature, and the influence of the main size of armature on the maximum current density and electromagnetic thrust of armature are obtained. At the same time, the optimal design of armature size is carried out by using matrix analysis method in orthogonal experiment. Finally, the optimized armature is verified by simulation. The results show that the optimized armature has the smallest maximum current density and the largest electromagnetic thrust in all size combinations.

1. Introduction

Electromagnetic railgun is a new concept weapon that uses electromagnetic force to launch projectiles. It breaks through the speed limit of traditional guns and can easily accelerate projectiles to several kilometers per second, thus destroying targets with great kinetic energy[1]-[3]. In recent years, in order to further enhance the killing efficiency and precision strike ability of electromagnetic railgun, scholars at home and abroad have begun to study the use of railgun to launch intelligent ammunition[4]-[6]. In the traditional bipolar orbital electromagnetic launcher, the electromagnetic field environment of the projectile location is bad, which can not meet the launching requirements of intelligent ammunition having high precision instruments. six-pole orbital electromagnetic launcher can make use of its own structural advantages to generate weak magnetic field in the armature center area to realize electromagnetic shielding protection for intelligent ammunition. At the same time, it can provide more electromagnetic thrust for armature at lower current, which has strong research significance.

Whether the traditional bipolar railgun or the six-pole orbital electromagnetic launcher, there are problems such as excessive concentration of armature current, ablation, melting and so on, which can reduce the service life and launch efficiency of the launcher[7]. Reasonable design and optimization of armature structure of six-pole orbital electromagnetic launcher will help to improve the uniform distribution of armature current, reduce the maximum current density, inhibit the occurrence of ablation, increase the electromagnetic force on armature, and improve the emission efficiency. Hughes[8] et al revealed the current distribution characteristics of armature with simple shape under steady state conditions. Satapathy[9] et al studied the effect of armature geometry change on magnetic
field and force. Ferrero R[10] et al studied the inductance gradient of the launcher and the distribution of current density in the armature.

This paper focuses on the influence of armature structure size change of six-pole orbital electromagnetic launcher on the maximum current density and armature force. orthogonal test is used to optimize armature structure to determine the optimal size of current distribution and armature force.

2. Basic principles of six-pole orbital launcher

The model of six-pole orbital electromagnetic launcher is shown in figure 1 and the cross section of orbital is shown in figure 2. During the launching process, the current flows into the 1, 3 and 5 orbits with symmetrical distribution of 120 degrees and equal spacing, and flows back to the 2, 4 and 6 orbits through the plum blossom shaped armature to form a closed loop. The circular magnetic field generated by orbital current interacts orthogonally with the current in armature, which generates Z-direction ampere force and promotes the armature to emit outward at high speed.

Assuming that the orbital current source point is \( S(x, y, z) \), the field point on the armature is \( P(x_1, y_1, z_1) \) [11]. The current element \( Idl \) located in the source point \( S \), so the magnetic flux density generated by the current element \( Idl \) at the field point \( P \) is

\[
dB = \frac{\mu_0 Idl}{4\pi R^3} d\times R
\]  

Among them, \( \mu_0 \) is the vacuum permeability, \( I \) is the intensity of the current flowing through the guide rails, \( R \) stand for \( S \) to \( P \) distance vector, 
\( R = (x_1 - x)i + (y_1 - y)j + (z_1 - z)k \).

Considering the skin effect, it is assumed that the current is concentrated on the inner surface of the orbital. According to the definition of surface current element, the current density on the orbital surface is known as \( J_s = I_s/d \) [12]. Assuming the current source point of rail 1 is \( S(-d, y, z) \), the field point on the armature is \( P(0, 0, z_1) \), which is on the center point of the armature. The thickness of armature is ignored in calculation. Rail 1 current element \( Idl = J_s dydzk \), 
\( R = di - yj + (z_1 - z)k \), 
\( R = \sqrt{d^2 + y^2 + (z_1 - z)^2} \).

\[
dB = \frac{\mu_0 Idl}{4\pi R^3} d\times R = \frac{\mu_0 J_s}{4\pi R^3} (ddydzj + ydydzi)
\]

\[
dB = dB_x i + dB_y j
\]
The scope of $z$ is $(0, z_1)$, the scope of $y$ is $(-\frac{b'}{2}, \frac{b'}{2})$. The magnitude of the magnetic induction intensity generated by rail 1 along the X axis $B_{1x}$ at the armature and along the Y axis $B_{1y}$ are as follows

$$B_{1x} = \frac{\mu_0 J_x}{4\pi} \int_0^{\frac{b}{2}} \int_0^{\frac{b}{2}} \frac{y}{\sqrt{d^2 + y^2 + (z_1 - z)^2}} dy dz$$

$$= \frac{\mu_0 J_x}{4\pi} \int_0^{\frac{b}{2}} \int_0^{\frac{b}{2}} \frac{d}{\sqrt{d^2 + y^2 + (z_1 - z)^2}} dy dz$$

$$B_{1y} = \frac{\mu_0 J_x}{4\pi} \int_0^{\frac{b}{2}} \int_0^{\frac{b}{2}} \frac{y}{\sqrt{d^2 + y^2 + (z_1 - z)^2}} dy dz$$

$$= \frac{\mu_0 J_x}{4\pi} \int_0^{\frac{b}{2}} \int_0^{\frac{b}{2}} \frac{d}{\sqrt{d^2 + y^2 + (z_1 - z)^2}} dy dz$$

It can be seen from figure 2 that rail 1 and rail 4 are symmetrical about the YOZ plane, so the magnetic field generated by the currents in rail 1 and rail 4 at point $P(0,0,z_1)$ in the x direction is zero, and the size in the Y direction is equal, the direction is the same. So we can solve the magnetic field of one rail in the Y direction, then multiply by 2. Supposing $B_{14}$ is the magnetic field at $P(0,0,z_1)$ generated by rail 1 and rail 4, then

$$B_{14} = (B_{1y} + B_{4y})j = 2B_{1y}j$$

Similarly, the magnetic field $B_{25}$ produced by rail 2 and rail 5 in $P(0,0,z_1)$, and the magnetic field $B_{36}$ produced by rail 3 and rail 6 in $P(0,0,z_1)$ are obtained. Because the current in each rail is the same size, the magnetic fields generated by each rail are equal in magnitude, as shown in figure 3.

![Figure 3](image)

**Figure 3.** Sketch map of magnetic field. The three vectors have the same size and in different direction. Electromagnetic shielding is realized in the armature center.

According to the geometrical relation, the magnetic field produced by the six rails is mutually counteracted, that is, the magnitude of magnetic field at the center of the armature is zero, which makes the magnetic field shielding in the center of the launcher to be realized, and is beneficial to the launching of intelligent ammunition.

3. **Simulation model and finite element analysis**

The armature model used in simulation is shown in figure 4, and the one-sixth model is selected as shown in figure 5. In order to simulate the launch process of a large volume object, $h = 0.2m$ is the thickness of armature head, length of tail is $d_t = 0.2m$ and thickness of tail is $d_o = 0.1m$, the fillet radius of the connection between the armature tail and the head is $r = 0.1m$. The total length of the rail is 4 m, and in cross section $a = 0.16m, b = 0.24m$. The armature material is aluminum and the material of the rail is copper.
Figure 4. Armature model. Loading zone is used to place smart ammunition like missile. Armature and rail meet through contact surface. The current is guided by the arc.

Figure 5. One-sixth of Armature model. It shows four main size of armature, including thickness of armature head, length of tail, thickness of tail and the fillet radius.

The peak value of pulse current applied in orbit is 500kA, and the maximum length of the grid of armature is 0.05m. The solution domain of vacuum boundary condition and 5 times model size are selected. Maxwell 3D module in ANSYS software was used to analyze the model. In this paper, the armature is mainly analyzed, and the current distribution cloud diagram of the armature surface is shown in figure 6, and the electromagnetic force of the armature is shown in table 1.

Figure 6. Current distribution cloud map. It shows that the current concentrate on the corner and the maximum current density is $2.6742 \times 10^7$ A / m$^2$.

Table 1. Electromagnetic force of armature.

| Electromagnetic force | Armature   |
|-----------------------|------------|
| $F_x$                 | 870N       |
| $F_y$                 | 4720N      |
| $F_z$                 | $2.13 \times 10^4$ N |
| Mag $F$               | $2.14 \times 10^5$ N |

It is easy to see from figure 6 that the current distribution on the armature is relatively uniform, and the current distribution is symmetrical about the center of the circle. The current is less distributed in the middle of the armature, and the darker area appearing at the connection between the tail fin and the armature main body is very small. The maximum current density appears in the corner area, and the
maximum current density is $2.6742 \times 10^7$ A/m$^2$. The armature is mainly subjected to the z-direction thrust, which propelling armature outward emission, and the interference force in the x and y directions is small.

Keep the other conditions constant. The maximum current density of armature and the variation of electromagnetic force can be obtained by changing the size of the armature, such as the head thickness, tail length, tail thickness and fillet radius, as shown in figure 7 and figure 8.

**Figure 7.** Change law of maximum current density. The above two figures show that the maximum current density change with four main structure of the armature.

It is easy to get from the figure that the maximum current density decreases with the increase of the thickness of the head, the thickness of the tail, and the radius of the fillet. By comparison, with the increase of radius, the maximum current density decrease amplitude is lower. The change in tail length has little effect on the maximum current density. The force of the armature increases with the increase of the thickness of the head and the thickness of the tail, and decreases with the increase of the fillet radius. The change of the length of the tail makes the electromagnetic force decrease first and then increase, but the change is small.

**4. Orthogonal test to optimize armature**

According to the experimental procedure of the orthogonal test, first determine the test index, factors and levels, the test indicators for the maximum current density and the electromagnetic force, there are four factors that affect the test index, there are three levels, the thickness of the head (A): 0.18m, 0.20m, 0.22m. Length of tail (B): 0.18m, 0.20m, 0.22m. Tail thickness (C): 0.09m, 0.10m, 0.11m. Corner radius (D): 0.09m, 0.10m, 0.11m. Secondly, select the appropriate orthogonal test table according to the factors and the number of levels. $L_9(3^4)$ orthogonal test table selected. Redesign the test plan and conduct the test. Fill the test results into table 2. According to the test results, the range
Finally, the test results are analyzed by matrix analysis method, and the armature size is obtained, which makes the maximum current density as small as possible and the electromagnetic force as large as possible.

Table 2. Orthogonal test scheme.

| Test Serial Number | A   | B   | C   | D   | Maximum Current Density ($\times 10^7$A/m$^2$) | Electromagnetic Force ($\times 10^5$N) |
|--------------------|-----|-----|-----|-----|---------------------------------------------|-------------------------------------|
| 1                  | 1   | 1   | 1   | 1   | 3.82                                        | 1.94                                |
| 2                  | 1   | 2   | 2   | 2   | 3.19                                        | 1.93                                |
| 3                  | 1   | 3   | 3   | 3   | 2.71                                        | 1.93                                |
| 4                  | 2   | 1   | 2   | 3   | 2.63                                        | 2.19                                |
| 5                  | 2   | 2   | 3   | 1   | 2.28                                        | 2.21                                |
| 6                  | 2   | 3   | 1   | 2   | 3.26                                        | 2.11                                |
| 7                  | 3   | 1   | 3   | 2   | 1.61                                        | 2.40                                |
| 8                  | 3   | 2   | 1   | 3   | 2.56                                        | 2.28                                |
| 9                  | 3   | 3   | 2   | 1   | 2.08                                        | 2.41                                |

Table 3. Range analysis table of maximum current density.

| Test Serial Number | A   | B   | C   | D   | $K_1$ | $K_2$ | $K_3$ | $R$ |
|--------------------|-----|-----|-----|-----|-------|-------|-------|-----|
|                    | 1.93| 2.18| 2.11| 2.19|       |       |       |     |
|                    | 2.17| 2.14| 2.18| 2.15|       |       |       |     |
|                    | 2.36| 2.15| 2.18| 2.13|       |       |       |     |
|                    | 0.43| 0.04| 0.07| 0.06|       |       |       |     |

Table 4. Range analysis table of electromagnetic force.

| Test Serial Number | A   | B   | C   | D   | $K_1$ | $K_2$ | $K_3$ | $R$ |
|--------------------|-----|-----|-----|-----|-------|-------|-------|-----|
|                    | 3.24| 2.69| 3.21| 2.73|       |       |       |     |
|                    | 2.72| 2.68| 2.63| 2.69|       |       |       |     |
|                    | 2.08| 2.68| 2.20| 2.63|       |       |       |     |
|                    | 1.16| 0.01| 1.01| 0.10|       |       |       |     |

By using the method of orthogonal test matrix analysis, the comprehensive weight matrix of the two performance indicators is obtained as follows

$$k=[0.1782 \ 0.2048 \ 0.2405 \ 0.0117 \ 0.0115 \ 0.0115 \ 0.0785 \ 0.0923 \ 0.1067 \ 0.0236 \ 0.0233 \ 0.0233]^T$$

$$=[A_1 \ A_4 \ A_4 \ B_4 \ B_4 \ B_4 \ C_1 \ C_1 \ C_1 \ D_1 \ D_1 \ D_1]^T$$

The greater the weight, the greater the impact on the results, so the optimal collocation scheme for the two performance indexes is $A_4 B_4 C_1 D_1$, the armature head thickness $h=0.22$m, tail length $d_s=0.18$m, tail thickness $d_0=0.11$m, corner radius $r=0.09$m. After the simulation of the optimized armature, the armature maximum current density is $1.6123\times 10^7$A/m$^2$, the electromagnetic force exerted on the armature is $2.43\times 10^5$N. Compared with other sizes of armature, the maximum current density and the electromagnetic force are all optimal.

5. Conclusion
In this paper, the model of Hexapole orbital electromagnetic launcher is established by using finite element analysis software Ansoft Maxwell, and the superiority of the model in launching intelligent ammunition is proved by theoretical analysis and simulation verification. Secondly, by changing the armature structure size of Hexapole track electromagnetic launcher, the effects of armature head thickness, tail length, tail thickness and fillet radius on armature current density maximum and
armature force are obtained. The maximum current density decreases with the increase of head thickness, tail thickness and fillet radius, and the change of tail length has little effect on the maximum current density. The armature force increases with the increase of the thickness of the head and tail, and decreases with the increase of the radius of the fillet. The armature force decreases first and then increases with the change of the length of the tail, but the change is not significant. Finally, the armature size is optimized by using the orthogonal test which takes the maximum current density and the armature force as the performance index. The optimum size of armature is the head thickness $h=0.22\text{m}$, tail length $d_s=0.18\text{m}$, tail thickness $d_o=0.11\text{m}$, corner radius $r=0.09\text{m}$. Simulation verification shows that the optimized armature has the smallest current density maximum and the largest electromagnetic force in all size armatures.

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