Comparison and Analysis of Electromagnetic Characteristics of New Quadrupole Track Electromagnetic Launcher

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Abstract. Electromagnetic railgun is the main research type of electromagnetic launcher. Researchers have found that the electromagnetic launcher with multipole track structure is capable of greatly improving the comprehensive performance of simple railgun. In this paper, a new quadrupole track electromagnetic launcher model is designed on the basis of simple railgun and quadrupole railgun. In order to fully analyze the electromagnetic characteristics of the model, the theoretical analysis of the structure is carried out at first. Then, under the same conditions as possible, the electromagnetic characteristics of it and the quadrupole railgun model are simulated and compared by using Ansys Maxwell simulation software. The results reveal that the new quadrupole track electromagnetic launcher model has the advantages of more concentrated magnetic field, more uniform armature current distribution and greater electromagnetic thrust.

1. Introduction

Electromagnetic railgun, referred to as railgun, is the main research type of electromagnetic launcher. It relies on the electromagnetic force between the track and armature to accelerate the projectile. It has many outstanding advantages, such as large kinetic energy, high speed, high precision, wide mass range of payload, good controllability and concealment, simple energy and low cost, safety and reliability. However, it also encounters various problems like high thrust and high current supply, extrusion, wear, planer, ablation and transition caused by assembly size and thermal expansion of armature and rail, sliding electrical contact between armature and rail, etc [1-3].

The structure of electromagnetic launcher plays a fundamental and decisive role in its performance. Therefore, the innovation of the structure of electromagnetic launcher is of great significance to promoting the practical application of electromagnetic launching technology. In order to achieve better comprehensive performance, researchers at home and abroad have done a lot of research on multipolar track electromagnetic launcher, among which plane augmented railgun and stacked augmented railgun are typical representatives. It has been discovered that the electromagnetic launcher with multipole track can provide greater electromagnetic thrust for the projectile and alleviate the obstruction of material and power supply technology. However, with the increase in the number of tracks, the structure of the model becomes very complex, which requires high processing technology, and the skin effect of current is more obvious. At the same time, a lot of Joule heat is generated in multiple tracks, resulting in a large amount of energy waste. Therefore, for the electromagnetic launcher, the relationship between the number of tracks and the performance of the launcher is not linear [4-6].
As early as the 1990s, some scholars had suggested the concept of small caliber plasma armature quadrupole railgun [7]. In recent years, more and more researchers have conducted a lot of research into the electromagnetic launcher model of quadrupole track structure. The static performance and transient dynamics of quadrupole track electromagnetic launcher are analyzed in reference [8-9]. The structural design and thrust simulation analysis of the enhanced quadrupole track electromagnetic launcher are carried out in reference [10]. The contact pressure between track and armature of quadrupole track electromagnetic launcher is simulated and analyzed, while the interference fit parameters between armature and track are optimized in reference [11-13]. In this paper, a new quadrupole track electromagnetic launcher model is designed on the basis of simple railgun and quadrupole railgun. The electromagnetic characteristics of the model are compared and analyzed by combining theory with simulation.

2. Modeling of the new quadrupole track electromagnetic launcher

2.1. Model structural analysis

The basic structure of the new quadrupole track electromagnetic launcher model is shown in figure 1. The model is symmetrical in structure, and the armature moves rapidly towards the outlet under the combined action of magnetic fields generated by four tracks of identical size and material. Current flows from the two tracks marked blue on the left, through the armature clamped in the upper and lower tracks, and then from the two tracks marked red on the right to form a closed loop. By applying pre-tightening force from four armature-rail contact surfaces, the structure can better maintain the high-speed sliding electrical contact between armature and rail, thus reducing the vibration during motion. By adding insulation materials, supporting materials and other auxiliary materials around the track form the launcher barrel, the left and right armature displacement can be prevented, and the overall stability of the model can be enhanced. Obviously, the model has various advantages, such as simple and stable structure, easy maintenance, convenient replacement of track and armature, etc.

![Figure 1. Structural schematic diagram of the new quadrupole track electromagnetic launcher](image)

2.2. Theoretical analysis of electromagnetic thrust

Prior to the analysis of the electromagnetic thrust of the model, it is necessary to construct the current and magnetic field coordinate system of the new quadrupole track electromagnetic launcher as shown in figure 2. In this coordinate system, the tail end faces of four rails are all in the XOY plane, the upper and lower rails are X-axisymmetric, and the left and right rails are Z-axisymmetric. The sizes of the four rails are the same. The distance between left and right tracks is $b$, the distance between upper and lower track is $d$, the width of the track is $a$, and the height of the track is $h$. $l(t)$ represents the length of the armature tail end face from the rail tail end face at $t$ time, and $m$ indicates the length of the armature. It is supposed that the source point of orbital current is $S(x, y, z)$, and that the field point of
armature is \( P(x', y', z') \). The current \( I \) is put into the tail end faces of the rail 1 and 3. Then the current in the end faces of the rail 2 and 4 is \(-I\).

![Figure 2. Current and magnetic field coordinates of the new quadrupole track electromagnetic launcher](image)

For current-carrying conductors, the line element vector is \(dl\), and the product of current \(I\) and \(dl\) flowing through a line element vector is called current element. Meanwhile, the direction of the current in the current element is taken as the direction of the line element vector. Then, we can regard a current-carrying wire as being connected by many current elements \(I \cdot dl\). Thus, the magnetic inductance \(B\) excited by a current-carrying conductor at a certain point in the magnetic field is the superposition of the magnetic inductance \(dB\) at that point by all the current elements of the conductor [10]. Therefore, when the track and armature are used as conductors, they ought to be calculated according to the volume current element.

Current density is a measure defined in the form of a vector. Its direction is the direction of the current, and its size is the current per unit cross-section area. The equation is expressed as \(\mathbf{J} = \frac{\mathbf{I}}{S}\). In the formula, \(\mathbf{J}\) represents the current density, \(\mathbf{I}\) indicates the current and \(S\) denotes the cross-section vector. Without considering the skin effect, under ideal conditions, the body current element in orbit is \(\mathbf{J}_v \times dxdydz\), \(\mathbf{J}_v = \frac{\mathbf{I}}{ah}\). The body current element in the armature is \(\mathbf{J}_v' = \frac{\mathbf{I}}{dm}\), \(\mathbf{J}_v' = \frac{\mathbf{I}}{dm}\). \(i, j, k\) represent the unit vectors in the direction of X, Y and Z axes respectively.

According to Biot-Savart's law, there are the following formulas

\[
d\mathbf{B} = \frac{\mu_0 (\mathbf{I} dl \times \mathbf{R})}{4\pi R^3}
\]

(1)

Among them, \(\mu_0\) represents vacuum permeability, and its value is \(\mu_0 = 4\pi \times 10^{-7}\) N·A⁻¹. If the coordinates of track 1 current source point are \(S_i(x, y, z)\) and armature field point are \(P(x', y', z')\), then there are

\[
d\mathbf{B}_i = \frac{\mu_0 (\mathbf{J}_v \times dxdydz \times \mathbf{R}_i)}{4\pi R^3}
\]

(2)

\[
\mathbf{R}_i = (x' - x)i + (y' - y)j + (z' - z)k
\]

\[
R_i = \sqrt{(x' - x)^2 + (y' - y)^2 + (z' - z)^2}
\]

(3)
\[
\mathbf{dB}_i = \frac{\mu_0}{4\pi R_i} J_v \, dx \, dy \, dz \, k \times [(x' - x)\mathbf{i} + (y' - y)\mathbf{j} + (z' - z)\mathbf{k}]
\]

\[
= \frac{\mu_0 J_v \, dx \, dy \, dz}{4\pi R_i^3} [(y' - y)\mathbf{i} + (x' - x)\mathbf{j}]
\]  

(4)

Therefore, the electromagnetic induction intensity produced by orbital 1 to field point \( P \) is as follows

\[
B_1 = \int_{x_0}^{(l')_m-a} \int_{y_0}^{(h')_m-a} \int_{z_0}^{(l')_m-a} \frac{\mu_0 J_v}{2\pi} [(y' - y)\mathbf{i} + (x' - x)\mathbf{j}] \, dx \, dy \, dz
\]

\[
= \frac{\mu_0 J_v}{4\pi} \int_0^{(l')_m-a} \int_{y_0}^{(h')_m-a} \int_{z_0}^{(l')_m-a} (y' - y)\mathbf{i} + (x' - x)\mathbf{j} \, dx \, dy \, dz
\]

(5)

The electromagnetic force at any point on the armature can be calculated by combining the current intensity of the armature. The electromagnetic force produced by track 1 on the armature field point is as follows

\[
d\mathbf{F}_1 = J_v' \, dx' \, dy' \, dz' \, \mathbf{i} \times \mathbf{B}_1
\]

(6)

When the armature acts as a current-carrying conductor, the ampere force acts on the whole armature area. Therefore, by integrating the whole armature volume, the electromagnetic propulsion force produced by track 1 on the armature as a whole can be derived as follows

\[
\mathbf{F}_1 = \int_{x_0}^{(l')_m-a} \int_{y_0}^{(h')_m-a} \int_{z_0}^{(l')_m-a} \frac{\mu_0 J_v' \, dx' \, dy' \, dz'}{2\pi} \mathbf{i} \times \mathbf{B}_1
\]

\[
= \frac{\mu_0 J_v' \int_{x_0}^{(l')_m-a} \int_{y_0}^{(h')_m-a} \int_{z_0}^{(l')_m-a} (y' - y)\mathbf{i} + (x' - x)\mathbf{j} \, dx \, dy \, dz}{2\pi}
\]

(7)

Due to the symmetry of the structure, the electromagnetic thrust of tracks 2, 3 and 4 is analyzed using the same method. The results are as follows.

\[
\mathbf{F}_2 = \mathbf{F}_3 = \mathbf{F}_4 = \mathbf{F}_1
\]

(8)

Therefore, the theoretical value of electromagnetic thrust generated by the launch model is

\[
\mathbf{F} = 4\mathbf{F}_1
\]

(9)

Its direction is along the Z axis.

3. Comparison and analysis of simulation

In order to perform analysis of the electromagnetic performance of the new quadruple track electromagnetic launcher more intuitively and deeply, the electromagnetic performance of the structure and the quadrupole railgun model are simulated and analyzed by using Ansys Maxwell simulation software under the same conditions to the greatest extent. Although the two models are quadrupole track structures, the model track layout, armature pre-tightening and current mode are completely different.

For convenience, the new quadruple track electromagnetic launcher model shown in figure 1 is called configuration 1, and the quadrupole railgun model shown in figure 3 is called configuration 2.
Figure 3. Basic model of configuration 2

Configuration 2 model is shown in figure 3. In this model, the structure, size and material of the four rails are the same, the armature is installed in the middle of the four rails, and the whole model is symmetrical about the geometric center of the armature. In the two relative rails, the same current of equal magnitude is introduced, which flows through the armature and finally flows out of the other two relative rails. The current in the guideway generates a quadrupole magnetic field area in the launching pipeline. The interaction between the magnetic field and the current in the armature generates thrust, which drives the armature forward rapidly, thus completing the launching of the projectile.

From the perspective of model structure, these two structures exhibit the characteristics of simple and stable structure, easy processing and replacement. From the point of view of model structure, these two structures have the characteristics of simple and stable structure, easy processing and replacement. Next, the electromagnetic characteristics of the model are analyzed in more depth from the perspective of simulation. The basic parameters of the simulation models of two quadrupole track electromagnetic launchers are shown in Table 1. Both models adopt copper track and aluminum armature. The armature is located 300 mm away from the rear end of the track. 100 kA impulse current excitation is applied to each model. Ansys Maxwell finite element simulation software is used. The two configurations are analyzed by appropriate solution domain and mesh size. The following simulation results are obtained:

Table 1. Basic parameters of simulation model.

| Parameter type               | Configuration 1 | Configuration 2 |
|------------------------------|-----------------|-----------------|
| Track length (mm)            | 500             | 500             |
| Track width (mm)             | 30              | 30              |
| Track height (mm)            | 30              | 30              |
| Upper and lower track spacing (mm) | 30          | 100             |
| Left and right track spacing (mm) | 100           | 100             |
| Armature length (mm)         | 40              | 40              |
| Armature width (mm)          | 160             | 100             |
| Armature height (mm)         | 30              | 100             |
3.1. Distribution of magnetic field between tracks

Figure 4. Distribution vector diagram of magnetic induction lines between tracks

(a) Configuration 1  
(b) Configuration 2

(a) Main view of configuration 1  
(b) Main view of configuration 2
As revealed by the figure above, the maximum magnetic induction intensity of configuration 1 is 2.756T and that of configuration 2 is 1.8763T. From figure 4, it can be seen that in configuration 1, the magnetic induction lines generated by the polar tracks are converged and strengthened between the tracks, which is due to the way that the structure passes through the same direction current at the same side of the tracks. Meanwhile, the magnetic field generated by the polar tracks cancels each other in the armature center region, and the distribution of magnetic inductance lines near the armature is relatively sparse because the current in the same direction is introduced into the relative tracks in configuration 2. Figure 5 shows that the magnetic field of configuration 1 is mainly concentrated between tracks and near armature, especially at the end of armature, and there is almost no divergence of magnetic energy around tracks. In configuration 2, magnetic field mainly concentrates between orbits. However, due to the offset effect of magnetic field, the magnetic field radiates to the outer side of the orbits, causing a large amount of magnetic energy dissipation. At the same time, the magnetic field in the armature region is weak, especially in the central region of the armature, which is not conducive to improving the force on the armature. Thus, the utilization rate of magnetic energy is not high. Therefore, configure 1 has a more concentrated magnetic field and less energy loss due to its unique structure and the way in which current is fed.
3.2. Armature current distribution

As indicated by the figure above, the maximum current density of armature in configuration 1 is $823.8894 \times 10^6$ A/m². Current is injected into armature from two tracks on the left side, which makes the current density in armature increase further without excessive current concentration. Meanwhile, the current distribution inside armature is quite uniform, which greatly inhibits the skin effect of current and is beneficial to the uniform force of armature in the process of high-speed movement. In configuration 2, the maximum current density of armature is $822.5034 \times 10^6$ A/m², which is small. However, due to the obvious tendency of choosing the shortest path to pass through the conductor, the phenomenon of current concentration occurs. In the mean time, the distribution of current in armature is dispersed, especially in the central region of armature, and there is almost no current. To a large extent, this results in the waste of energy and materials, and the consistency of armature force is also affected to a certain extent. Therefore, the armature current distribution of configuration 1 is more uniform, and it has certain advantages in armature stable force and restraining current concentration effect.

3.3. Electromagnetic thrust

The electromagnetic thrust produced by the two types of quadrupole track electromagnetic launchers at a time when 100kA pulse current excitation is applied to each model is shown in Table 2 below.

| structure type | F(x) /N | F(y) /N | F(z) /N | Mag(F) /N |
|----------------|---------|---------|---------|-----------|
| Configuration 1| 7.013   | 0.1015  | 11240   | 11240     |
| Configuration 2| 3.7239  | 10.106  | 4747.2  | 4747.2    |

In the actual process of movement, the force on armature is unlikely to be completely uniform, which leads to the existence of X-axis and Y-axis transverse forces in both configurations, but the numerical values are very small. As compared to configuration 1, the transverse force of configuration 1 is smaller, for which the impact on track is smaller. It is confirmed from another point of view that the force on configuration 1 armature is more consistent. The axial force produced by configuration 1 is 11240N, and that produced by configuration 2 is 4747.2N. Under the same current excitation, the electromagnetic thrust produced by configuration 1 is 2.37 times that in configuration 2.

In order to compare and analyze the change of thrust with current of each model more comprehensively, the scanning settings of current parameters are created by using simulation software.
[11], and the curve of thrust with current of each model in the range of $[0,300]$ kA is obtained as follows:

![Figure 7. The relationship between electromagnetic thrust and current](image)

The basic parameters of configuration 1 simulation model and related modeling data are substituted by formulas (7), (8). After calculation, the red curve shown in figure 7 is obtained, which represents the curve of theoretical value of electromagnetic thrust varying with current. From figure 7, it can be seen that the electromagnetic thrust of each model increases with the increase of current, and the magnitude of the increase of configuration 1 is larger than that of configuration 2, which indicates the higher energy utilization of configuration 1. In addition, without considering the actual losses such as Joule heat and friction heat, the simulation results of configuration 1 electromagnetic thrust are similar to the theoretical values, which highlight the advantages of configuration 1 in electromagnetic thrust and energy utilization.

The simulation results of electromagnetic thrust are consistent with the analysis results of magnetic field distribution between tracks and armature current distribution, which further validates the excellent electromagnetic comprehensive characteristics of configuration 1.

4. Conclusion

Based on the simple rail gun and the four-rail gun, a new type of quadrupole rail electromagnetic launcher model is designed in this paper. The theoretical and simulation analysis shows that the configuration has the following advantages: firstly, the structure is simple and stable, and it is easy to realize in engineering; secondly, the magnetic field distribution is concentrated, and the magnetic energy utilization rate is high; thirdly, the uniform distribution of armature current can better keep armature moving smoothly and restrain the current concentration effect; fourthly, it can generate greater electromagnetic thrust under smaller current excitation, which reduces the dependence of electromagnetic launcher on power supply technology.

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