Research Article

Calculation Method of Projectile Movement Characteristics for Complex Structure Railgun

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Electromagnetic railgun is a launcher that relies on electrical energy to do work to propel a projectile to high speed. In the military application of railgun, the acquisition and adjustment of projectile movement characteristics, including acceleration and velocity, are very important. In order to realize the rapid calculation of the projectile movement characteristics and the precise adjustment of the thrust, the force and projectile movement characteristics for a complex structure railgun, augmented quadrupole hyperbolic railgun, were studied by the method of field-circuit coupling. Based on Biot-savart Law and accurate fitting of current distribution, the electromagnetic characteristics and force characteristics of the launcher are analyzed, and the iterative method is used to realize the coupling between the pulse forming network and the calculation of the force on launcher and finally solve the movement of the launcher projectile characteristic. Comparing the calculation and experiment, the error of speed calculating with this method is small in the low speed stage.

1. Introduction

Electromagnetic railgun is a device that uses high-power supply as an energy source and can efficiently convert high-power electrical energy into kinetic energy in an instant. Compared with the gunpowder launch, the railgun has the advantages of stable operation, good repeatability, accurate and adjustable thrust, and short launch interval. Therefore, it has a broad application prospects in the field of air defense against UAV swarm targets. The combat against UAV swarm targets needs to accurately and quickly adjust the bursting speed of the projectile according to the target movement characteristics. Therefore, it is necessary to study the rapid calculation method of the projectile movement characteristics of the launcher.

At present, the fast calculation of projectile movement characteristics is mainly carried out by analyzing the conversion process of power supply electric energy and armature kinetic energy. This method can only solve the thrust on the armature, and the solution accuracy depends on the acquisition accuracy of the railgun inductance gradient. For the acquisition of the inductance gradient of the railgun, Grover and Grover [1] theoretically deduced the calculation method of the inductance gradient of the railgun with simple structure [2–4]. Moyama and Fukumoto [5] and Ying et al. [6] explain the finite element simulation with theoretical calculation and had a deeper understanding of the research results of Grover and Grover [1] et al. Keshtkar and Bayati [7] experimentally measured the performance of different rail materials of the launcher during the working process [8]. For a railgun with a relatively simple structure, the method proposed in the above research has been able to quickly obtain accurate inductance gradient. But for the electromagnetic railgun with complex structure, the above method is difficult to apply. In addition, for a specific railgun structure, the above research can only calculate the relationship between the inductance gradient and the position of the armature. To calculate the movement characteristics of the armature through the inductance gradient, the above method no longer work. It is necessary to obtain the relationship between the inductance gradient and the working time of the railgun or use a fixed inductance gradient as approximation. This paper proposed
a new method which is suitable for the calculation of the force of the railgun with complex structure and can solve the law of motion characteristics with time.

In this paper, the force and armature movement characteristics of the augmented quadrupole hyperbolic electromagnetic railgun are studied, and the current distribution of the railgun is analyzed based on the electromagnetic field diffusion equation. Magnetic field distribution and the force of the railgun are calculated according to Biot-Savart Law. On this basis, by coupling the response of the pulse forming network and the force of the railgun through an iterative method, a high-precision and fast calculation method for the projectile movement characteristics of the railgun is obtained, which can provide a basis for the adjustment of the speed of the electromagnetic railgun projectile, and finally lay the foundation for the application of railguns in the field of air defense. Finally, the calculation results are verified by comparing with experiment.

2. Armature Force Calculation Method

2.1. Parameters of the Model. The electromagnetic railgun system consists of launcher, armature, pulse power supply, charger, control system, etc., as shown in Figure 1.

This paper mainly analyzes the physical phenomena that occur in the bore of the launcher, including armature-rail system, insulating parts, and fasteners, without considering energy supply, transmission, conversion, signal acquisition, and other systems. The armature-rail system includes the curved main rail, square augmented rail, and the interference armature; the G10 insulating baffle in the bore is simulated by adding electrical insulation boundary conditions, the rigid constraint boundary condition simulation is applied to simulate the fasteners, and the power is loaded directly to the end of the rails.

The main rails of the augmented quadrupole hyperbolic railgun are distributed in a 90° array and are symmetrically installed around the armature, which not only helps to maintain the stability of the launcher but also forms a symmetrical magnetic field to ensure that the launcher is evenly stressed [9]. The currents between the two opposite main rails are equal in amplitude and in the same direction, and the currents are in opposite directions between the two neighboring main rails. The main rail and the corresponding augmented rail currents flow in the same direction, as shown in Figure 1.

The main view of the armature-rail system is shown in Figure 2, which only shows one pair rail of the launcher.

The structure parameters of the launcher are shown in Table 1.

The materials of the main rail, augmented rail, and armature are the C18150 copper, T2 copper, and 6061 aluminum, respectively. The material parameters are shown in Table 2.

2.2. Calculation Theory. The Biot-Savart Law expresses the magnetic field excited by a current source at any position in space as follows:

\[
\frac{dB}{dB} = \frac{\mu_0}{4\pi} \frac{I d l \times r}{r^3},
\]

where permeability of vacuum \( \mu_0 = 4\pi \times 10^{-7} N \cdot A^{-2} \).
where $d$ is the integral of discrete scale; its physical meaning is the area of each discrete region. Therefore, the magnetic flux density excited at point $P(x, y, z)$ is

$$B_i = \mu_0 \int_{S_i} dx dy \left( \cos \theta_1 - \cos \theta_2 \right) 
\quad \text{where } S_i \text{ is the area of the rail end face, which can be obtained according to the geometry of the model.}
$$

$$F = \int_{V} f \times \sum_{k=1}^{n} B_k dV,
\quad \text{where } I_A \text{ is the current density on the armature and the integral area } V \text{ is the current-carrying region on the rail. For the augmented rail, it is the entire rail. For the main rail, it is the area where access the circuit and it will change with the movement of the armature.}
$$

$$F_k = \int_{V} f_{i} \times \left( \sum_{k=1}^{n} B_k - B_l \right) dV,
\quad \text{where } F_k \text{ is the magnetic flux density excited by the other rails. In the case of ignoring the end effect of the rails and the influence of the armature, it can be described as follows:}
$$

$$F = \int_{V} f \times \sum_{k=1}^{n} B_k dV,
\quad \text{and the force of the entire railgun model can be calculated,}
$$

$$3. Analysis of the Electromagnetic Field Distribution

3.1. Current Distribution. Based on the above analysis, it can be seen that the key to solving the force of the launcher according to Biot-Savart Law is to obtain the precise distribution of the current density on the armature and the rail.
The most common for solving the skin depth law by applying the semi-infinite plane assumption, we can obtain the current density distribution on the rail and the augmented rail, the skin depths are relatively close, and the current density distribution is basically the same.

In Figure 4(a), it can be seen that in all directions of the main rail and the augmented rail, the skin depth is only about 1.1 mm, so it is reasonable to calculate the skin depth on the basis of the assumption of a semi-infinite plane.

When the skin depth is much smaller than the rail cross-sectional area, we can obtain the current density distribution law by applying the semi-infinite plane assumption that is the most common for solving the skin depth

\[ J_x(x, t) = J_0 e^{-\sqrt{\mu\sigma/\delta_x}} \cos \left( \sqrt{\mu\sigma/\delta_x} - \omega t \right). \]  

where \( \omega \) is the frequency of the current. \( J_0 \) can be calculated according to the following:

\[ J_0 = \frac{I}{\left( \int_0^\delta e^{-\sqrt{\mu\sigma/\delta_x}}dr \right)^2}. \]

It is easy to know that when \( x = \sqrt{2/\mu\sigma\omega} \), \( J = J_0/e \), define the \( x \) at this situation as the skin depth, denoted as \( \delta \). Within the skin depth, the magnitude of the current density decays exponentially.

According to Equation (9), how the current diffuses in space is related to the frequency of current. Therefore, in order to obtain the variation of the current skin depth with time, it is necessary to analyze the excitation source of the railgun. Figure 5(a) shows the time-amplitude curve of the current measured by the Rogowski coil during the working process of the railgun. For the Joint Time-Frequency Analysis of the current, a wavelet transform is carried out. The result of the analysis is the graph of the excitation current time-frequency as shown in Figure 5(b). It can be seen that within 0.23 ms when the capacitor just begins to discharge and the current is in the rising, the frequency of the current decreases sharply, from 3900 Hz to 3300 Hz, and then, the frequency remains stable.

Figure 5(d) shows the skin depth on the paths shown in Figure 4(a) as a function of time; Figure 5(c) shows the variation of the skin depth with time calculated according to Equation (9) and the mean value of the of the skin depth on the paths. It can be seen that the theoretical calculation results are close to the simulation results. Compared with the size of the main rail and the augmented rail, the skin depth is only about 1.1 mm, so it is reasonable to calculate the skin depth on the basis of the assumption of a semi-infinite plane.

Based on the above analysis, this paper uses the method shown in Figure 6 to simplify the current density distribution on the rail; that is, in the region shown in Figure 6(b), the current density distribution is fitted according to the principle suggested by Equation (9).
Figure 7 shows the cloud chart of the current density distribution in the armature region obtained by simulation. As can be seen from Figure 7(c), the current density distribution in the armature region is relatively complex. The electromagnetic thrust that pushes the armature forward is provided by the components of the current on the armature in the $x$ and $y$ directions, as shown in Figures 7(a) and 7(d). It can be seen that the distribution scale of this component in the $z$ direction is much smaller than the rail length, and the distribution in the $x$ and $y$ directions is relatively regular. Therefore, the current distribution principle in the armature area can be fitted as follows:

1. In the $z$ direction, the current density is assumed to be uniformly distributed in the armature head.

2. In the $x$ and $y$ directions, it can be simplified according to the method shown in Figure 8(b).

The current density in the armature region is calculated by this method as $J_A = I/2\pi \delta$.

3.2. Magnetic Field Distribution. Based on the above analysis, the principle of magnetic field distribution in space is obtained by using Biot-Savart Law, as shown in Figure 8. Among them, Figures 8(a)–8(c) show the cloud chart of the magnitude values of the magnetic field strength in the $x$ and $y$ directions on several sections parallel to the rail's surface. The section positions are as follows: armature throat section (a), armature rear section (b), and armature front section (c). Figure 8(d) shows the magnetic field strength in the $x$, $y$, and $z$ directions at section (a).
It can be seen that, in front of the armature, an electromagnetic shielding area is formed in the launcher bore, and the magnetic field is mainly distributed between the main rail and the augmented rail. Behind the armature, the magnetic field is stronger and can provide enough thrust for the armature movement. At the armature throat, although the magnetic field strength components in the \( x \) and \( y \) directions are small, the total magnetic field strength is relatively large, indicating that the magnetic field distribution in this area is complex and easy to generate electromagnetic interference.

Based on the above analysis about the magnetic field distribution and current density distribution, further, the relationship between the thrust on the armature and the current amplitude and the relationship between the thrust and the position of the armature can be obtained, as shown in Figure 9.

Figure 9(a) shows the contribution of the main rail and the augmented rail to the thrust of the armature under the current amplitude of 400 kA, respectively. It can be seen that the thrust remains basically constant after the armature is far...
from the end of the end of the rail by a distance of one caliber. This phenomenon is slightly different from the conclusion of the “quadruple caliber” rule drawn by Wang Ying’s research on general railgun [11], indicating that the augmented quadrupole hyperbolic railgun can reach the thrust peak earlier, and the acceleration effect on armature better, the movement of the armature in the bore will be smoother.

Figure 9(b) shows the relationship between the thrust on the armature force with armature position and current amplitude.
armature and the current amplitude when the armature is loaded in the muzzle. It can be seen that the thrust provided by the main rail is much larger than that provided by the augmented rail when the same current is used for excitation. It is not only due to the different structures of the main rail and the augmented rail but also because the augmented rail is far from the armature.

4. Analysis Based on Field-Circuit Coupling Study

4.1. Response of the PFN. The work of the electromagnetic railgun relies on the high-power supply. The PFN structure used in the augmented quadrupole hyperbolic railgun test platform studied in this paper is shown in Figure 10, where \( U_C = 5000 \text{ V}, \ R_C = 3 \text{ m\Omega}, \ L_C = 5 \mu\text{H}, \ C = 1750 \mu\text{F}, \ L_D = 20 \mu\text{H}, \ R_D = 0.3 \text{ m\Omega}, \) and \( L_R \) and \( R_R \) are the inductance and resistance of the railgun armature-rail system itself. According to the conduction state of the flyback branch, the discharge process of the pulse capacitor can be divided into two stages, as shown in Figures 11(a) and 11(b). According to Kirchhoff’s Voltage Law, the equation for two working stages can be obtained as follows:

\[
(L_C + L_R)\frac{d^2u_c}{dt^2} + (R_C + R_R)C\frac{du_c}{dt} + u_c = 0, \tag{11}
\]

\[
d^2i_C \over dt^2 + \frac{R_C + R_D}{L_C + L_D} di_C \over dt + \frac{1}{(L_C + L_D)} di_C \over dt = 0.
\]

The resistance of the armature-rail system of the railgun is small, and the circuit works in an underdamping state, so the responses of the two stages of capacitor discharge are as follows:

\[
i_R(t) = \frac{U_0}{a_1(L_C + L_R)} e^{-bt} \sin (at), \tag{12}
\]

\[
i_R(t) = I_0 e^{-b(t-a_0)},
\]

where

\[
a = (R_C + R_D)/(2(L_C + L_D)), \quad b = \sqrt{[1/(L_C + L_D)] - a^2}.
\]

4.2. Armature Movement Calculation. During the working of the railgun, the length of the rails connected to the circuit changes constantly, so he loads \( L_R \) and \( R_R \) of the circuit also change constantly, and the rate of change is related to the armature movement. Therefore, to solve the response of the PFN, it is necessary to calculate the movement of the armature.

At a certain moment in the working of the railgun, the position of the armature, the amplitude of the excitation current, and the instantaneous frequency of the excitation current are all determined. These three parameters are a set of initial values for the solution method introduced in Section 2. According to the solution method introduced in Section 2, a set of determined initial values can uniquely determine

the thrust on the armature as follow:

\[
F_{\text{thrust}} = f(I_t, \delta(x), x_t).
\]

According to the Lorentz Force formula, the electromagnetic force is proportional to the square of the current amplitude, so the current amplitude can be regarded as an independent variable, and then, the relationship between the armature force and the skin depth \( \delta \) and armature position \( x \) can be discussed.

Define the armature force factor \( m(\delta(t), x(t)) \), which can be expressed as follows:

\[
m(\delta(t), x(t)) = \frac{F(t)}{P(t)}.
\]

According to the method described in Section 2, the value of the armature force factor \( m \) can be obtained when the armature position and current skin depth are determined, as shown in Table 3.

By solving the response of the PFN, the current amplitude of the circuit under a specific load can be determined, and the load is related to the position of the armature; then through Joint Time-Frequency Analysis; the current frequency and skin depth corresponding to the current amplitude can be obtained. The position of the armature is affected by the movement of the armature at the previous time, and it is related to the excitation current, which can be expressed as follows:

\[
x_t = g(I_{\text{thrust}}, \delta_{\text{thrust}}, x_{\text{thrust}}).
\]

Based on the above analysis, according to the iterative method shown in Figure 10, the variation of the force on the railgun and the movement of the armature with time can be obtained.

Figure 12 shows the results obtained by this method. Among them, Figure 12(a) shows the electromagnetic thrust on the armature and the lateral force on the main rail and the augmented rail. Figures 12(b)–12(d) show the acceleration, velocity, and displacement of the armature moving in the bore calculated and simulated by the above method, respectively. The installation position and measurement results of B-dot in the experiment are also marked in Figure 12. It can be seen that the armature movement state calculated by the above method is in good agreement with the simulation and experiment, indicating that this method is more reliable in calculating the armature movement. It can be seen from Figure 12(a) that the decay rate of the lateral force on the main rail is lower than the decay rate of the thrust on the armature. The reason is that with the movement of the armature, the part of the main rail connected to the circuit gradually increases, which is consistent with Igenbergs’ research conclusion [12].
Table 3: Table lookup data required in iterative calculation.

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<th>Skin depth/(mm)</th>
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Figure 10: Flow chart of armature movement calculation iteration process.

Figure 11: Pulse forming network of the railgun's power.
5. Conclusion

In this paper, on the basis of analyzing the current distribution in the working process of the railgun, the magnetic field distribution and force of the augmented quadrupole hyperbolic electromagnetic railgun are calculated according to Biot-Savart Law. The field-circuit coupling study for the railgun is carried out by an iterative method, and the results are compared with the experiment. The results show the following:

(1) The method proposed in this paper can realize the rapid calculation of the force and the movement of the armature in complex railgun structure according to the parameters of the railgun’s power supply circuit and the railgun structure. According to the method proposed in this paper, the precise adjustment of the projectile velocity can be achieved, which will maximize the advantage of the railgun.

(2) The augmented railgun structure can effectively improve the electromagnetic thrust on the armature, but due to the influence of electromagnetic interaction, the current distribution on the rail is different from that of the nonaugmented railgun. The strength of the magnetic field between the main rail and the augmented rail is relatively large, and it is necessary to strengthen the insulation measures between the rails.

(3) In order to make the armature force uniform, the railgun has strict symmetry in structure, so this feature can be used to simplify the model during calculation. This feature can be used in the design to achieve electromagnetic shielding in the bore of the railgun and improve the railgun performance.

The method proposed in this paper is suitable for the calculation of the projectile movement characteristics and force of the electromagnetic railgun with complex structure. Through this method, the speed of the armature can be quickly adjusted according to the power supply parameters.
which will promote the application of railguns in air defense operations. Since the calculations carried out in this paper are all in the low-speed stage of the railgun’s working, the armature ablation and rail damage caused by the high-speed movement of the armature and the changes in the contact resistance cannot be fully considered. In the future, we will conduct multiple experiments to determine a reasonable empirical factor that takes into account ablation and rail damage appearances as a supplement to the proposed method.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no competing interest.

References