Analysis of electromagnetic characteristics of a new electromagnetic ejection device

Shi-da REN1*, Gang FENG1, Teng-da LI1, Hui YANG2

1Air and Missile Defense College, Air Force Engineering University, Xi’an shan xi 710051, China 
2Northwest University, Xi’an shan xi 710127, China

*Corresponding author’s e-mail: 23045392@qq.com

Abstract. Electromagnetic ejection technology is a new launching technology which uses electromagnetic force to accelerate the projectile to ultra-high sound speed. This technology can break through the speed limit of traditional gunpowder launching, and realize the accurate control of exit speed by controlling the excitation pulse current.

Four track electromagnetic launcher is a special enhanced electromagnetic launcher, which has many advantages that dual track electromagnetic launcher does not have. Its development greatly promotes the application of electromagnetic launch technology in aerospace field. In this paper, according to the practical needs of electromagnetic space launch technology, a simple four orbit electromagnetic launch device is designed and established; the finite element analysis of the model is carried out, and the electromagnetic and current characteristics are simulated, and the skin effect and proximity effect of current are obviously observed; the theoretical analysis and formula derivation of inductance gradient are carried out, and finally two kinds of inductance gradient are proposed based on the finite element theory simulation A simple example is given.

1. Introduction

Electromagnetic track launcher is usually composed of track, armature, insulator shell and high frequency pulse power supply. This paper makes a theoretical analysis of the electromagnetic rail launcher, focusing on the structural characteristics, working mode and basic principle of the four rail electromagnetic gun. The finite element simulation and analysis are carried out.

2. Modeling of four-rail electromagnetic launcher

In this paper, the original 3D model parameters are: the caliber of gun body is 700mm×700mm, track thickness ω is 100mm, track heighth is 200mm, the axial length of armature is 400mm, the axial thickness is 150mm (other models in this paper are analyzed on this basis). After modeling, import it into Ansys Electronics, the armature is made of pure aluminum (the conductivity is 3.76×10^7 S·m⁻¹), the track is made of brass (the conductivity is 5.8×10^7 S·m⁻¹). The specific parameters are as follows:
Table 1 material parameters of four rail electromagnetic launcher

| Parts                  | Material       | Density/$(kg \cdot m^{-3})$ | Permeability | Conductivity/$(S \cdot m^{-1})$ | Resistivity/$(\Omega \cdot m)$ |
|------------------------|----------------|------------------------------|--------------|---------------------------------|-------------------------------|
| Track                  | brass          | $8.66 \times 10^3$          | 1            | $5.8 \times 10^7$               | $5.4 \times 10^{-8}$          |
| Armature               | pure aluminum  | $2.6989 \times 10^3$        | 1            | $3.76 \times 10^7$              | $2.6548 \times 10^{-8}$       |
| Hollow part of gun body| vacuum         | -                            | 1            | -                               | -                             |

SolidWorks software is used to conduct three-dimensional modeling of the four rail electromagnetic launcher, as shown in Figure 1,2:

![Figure 1 Orbit model](image1)

![Figure 2 Armature model](image2)

Permeability is a kind of physical quantity used to express the magnetism of magnetic medium. It reflects the ability of conducting magnetic lines of force in a magnetic field after current is introduced into a conductor in space. In general, the permeability of the conductor is approximately 1. In this paper, the permeability has little influence on the analysis of the factors affecting the inductance gradient, so the permeability of copper, aluminum and vacuum is set as 1.

3. Analysis of electromagnetic characteristics of four rail electromagnetic launcher

Based on Maxwell equations and electromagnetic field theory, the closer to the guide rail, the greater the magnetic field intensity, while the magnetic field intensity in the emission center is zero. It is easy to know that the current near the guide rail will have a great influence on the thrust of the launcher, so it is very important to keep a good contact between the guide rail and the armature, and the central area is suitable for loading precision instruments or launching devices and preventing them from strong magnetic field interference.

![Figure 3 Magnetic field distribution](image3)
The electromagnetic field cloud image is obtained by Maxwell simulation, and the numerical simulation results are consistent with the theoretical analysis results of electromagnetic field. The electromagnetic force vector diagram is as follows:

![Cross section electromagnetic distribution](image)

It can be concluded from the distribution of magnetic field between the guide rails that the magnetic field between the two adjacent guide rails is also large except for the guide rail. It proves the feasibility and superiority of armature structure design, that is, the armature structure features make the current flow through the strong magnetic field area in the armature more intensively, which strengthens the armature thrust; and the zero magnetic field between the central area of the armature and the emission area is hollow. The field area corresponds to the thrust and does not cause obvious loss to the thrust.

4. Current characteristic analysis

The current distribution in the guide rail will affect the force and heat source distribution in the guide rail. The cloud chart of current distribution can be observed in ANSYS electronics as shown in the figure. The skin effect and proximity effect of current can be clearly observed from the figure.
Figure 5 Skin depth at different armature positions

The current is concentrated on the rail and armature surface. It can also be seen from the above figure that the closer the armature is to the muzzle, the shallower the skin depth of the current.

5. Inductance gradient analysis and its calculation method

Based on the basic principle of electromagnetism, the electromagnetic thrust of the electromagnetic orbit launcher is associated with the driving current. The expression is as follows.

\[ F = \frac{1}{2} LI^2 \]  

(1)

Where \( I \) is the driving current and \( L' \) is the inductance gradient, so the thrust \( F \) of the launcher can be measured by the inductance gradient \( L' \).

According to the electromagnetic thrust calculation formula, the inductance gradient is an important parameter for the design of electromagnetic orbit launcher, which affects the electromagnetic force of the armature, the exit speed of the missile and the setting of the structural parameters of the launcher. Therefore, the analysis of the influencing factors of the inductance gradient is of great significance. In order to accurately study the influencing factors of inductance gradient, firstly, the formula is deduced. Secondly, based on the above model, further simulation analysis is carried out in two aspects of armature and non-armature. Finally, the inductance gradient is calculated by impedance matrix or virtual work principle.

5.1. Without armature

When there is no armature, because the current distribution on the guide rail is consistent, the gradient of inductance on the track with distance can be ignored. The average inductance gradient of the track can be further calculated by solving the self-inductance and mutual inductance coefficient of the track with the finite element simulation method.

When there is no armature, pay attention to load current at both ends of the guide rail, and the
current value on the same guide rail is the same, and the direction is opposite. The impedance matrix without armature is obtained as follows:

![Impedance matrix without armature](image)

From the impedance matrix, the impedance of each guide rail is before each data comma, and the inductance is after comma, and the main diagonal is self-sensing (Current1,Current1, Current2, Current2, Current3, Current3, Current4, Current4), the others are mutual inductance between guide rails.

According to the formula of electromagnetic force, the approximate formula of inductance gradient without armature is deduced:

$$L' = \frac{L + M}{l}$$

The data solution in the impedance matrix is as follows:

$$L' = \frac{l_1 + l_2 + l_3 + l_4 + 2(l_{12} + l_{13} + l_{14} + l_{23} + l_{24} + l_{34})}{l} = 0.99365 \mu H/m$$

The inductance gradient without armature is obtained 0.99365 μH/m.

5.2. Armature condition

In the case of armature, the armature is modeled, and the inductance gradients at different positions of the armature are obtained based on the principle of virtual work. The armature moves between the guide rails under the action of radial electromagnetic force. According to the principle of virtual work, if the virtual displacement of armature is DX, the energy relationship is as follows:

$$\begin{cases}
    dW_i = dW_h + dW_a + dW_o \\
    dW_a = Fdx \\
    F = \frac{L' I^2}{2}
\end{cases}$$

Among, \(W_i\) is the total energy input to the launcher; \(W_h\) is the increase of magnetic field energy; \(W_a\) is the energy transmitted to the armature; \(W_o\) is the energy lost in the form of thermal effect; \(L'\) is the inductance gradient of the launcher; \(F\) is the electromagnetic force received by the armature; \(I\) is the current input.

$$dW_i = dW_h + dW_a + dW_o$$

It is assumed that in the process of virtual displacement, the power supply does not output energy to the magnetic field, so \(dW_h=0\). If the solution domain is set to infinity, then \(dW_o=0\).

Then, the total energy input to the launcher can be regarded as the total energy used to push the armature to do work.

$$dW_i = \frac{L' I^2}{2} dx$$

Therefore, the calculation formula of inductance gradient can be simplified as follows:
\[ L' = \frac{2dW_i}{I^2 dx} \]  

The total energy in the transmitter can be obtained by viewing the result data in Maxwell, and then the inductance gradient can be solved by the formula.

6. Summary
The main work of this paper is reflected in the following aspects:

1. Based on the practical needs of electromagnetic space launch technology, a simple four orbit electromagnetic launch device is designed and established;

2. Based on the finite element analysis theory, the electromagnetic and current related computer simulation is carried out for the established four rail electromagnetic emission model. According to the simulation results, the superiority of armature design is verified, and the current skin effect and proximity effect are obviously observed. The simulation results accord with the electromagnetic theory analysis;

3. In this paper, the inductance gradient, which is an important parameter to determine the performance of electromagnetic rail launcher, is theoretically analyzed and derived. Finally, two calculation methods of inductance gradient are proposed based on the finite element theory simulation, and a simple example is given.

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