Simulation Analysis of Inductance Gradient of Series Enhanced Four-Rail Electromagnetic Launcher

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Abstract. In order to study the characteristics of inductance gradient of series enhanced four-rail launcher, a three-dimensional simulation model of series enhanced four-rail launcher is built based on the theoretical calculation formula of inductance gradient of series enhanced four-rail launcher. The effects of armature position, time harmonic analysis frequency and the parameters of main and secondary rails on the inductance gradient under the influence of armature are analyzed by finite element method. The simulation results show that the inductance gradient of the series enhanced four-rail launcher is negatively correlated with the distance between the armature and the tail of the rail, the frequency of time-harmonic analysis, the distance between the main and secondary rails, the height and thickness of the secondary rails.

1. Introduction

Electromagnetic launch technology is a new weapon launch technology which converts electromagnetic energy into overload kinetic energy and can promote overload to high speed[1-2]. To realize the ultra-high speed motion of overload, the electromagnetic launcher must have enough electromagnetic thrust. The thrust lifting of conventional electromagnetic launcher can be realized by increasing the pulse current, and the pulse high current will bring about a series of problems such as rail ablation and sharp increase of resistance[3-4]. Therefore, the series enhanced four-rail electromagnetic launcher is proposed by relevant scholars. The series enhanced four-rail electromagnetic launcher is to add one or more secondary orbits to the outer layer of each main orbit of the ordinary launcher to provide stronger electromagnetic thrust[5-6].

Among the parameters of the series enhanced four-rail electromagnetic launcher, the inductance gradient is very important, which is related to the magnitude of the electromagnetic thrust on the armature and the launch efficiency of the electromagnetic launcher. Scholars at home and abroad have carried out a large number of theoretical and experimental studies on the inductance gradient of electromagnetic launcher. Kerrisk[7]proposed inductance gradient formula at high current frequency at the beginning of electromagnetic launch; Grover[8]studied the inductance gradient calculation method at low current frequency at steady state; Liqiang Sun[9]analyzed the variation law of orbital inductance gradient with current frequency; Siyuan Tong[10]analyzed the influence of inductance gradient on rail geometry parameters and armature position of ordinary four-rail electromagnetic launcher orbit. However, the influence of armature on inductance gradient of electromagnetic launcher system has not been studied deeply.

Based on the above analysis, a three-dimensional simulation model of series enhanced four-rail
electromagnetic launcher is established in this paper. The inductance gradient of series enhanced four-rail launcher is calculated by finite element simulation. The influence of armature position, current frequency and different main and secondary rail parameters on inductance gradient is analyzed, which provides a reference for the design and optimization of series enhanced four-rail electromagnetic rail launcher.

2. Calculation method of inductance gradient

2.1. Theoretical calculation

Theoretical calculation of inductance gradient of simple rectangular rail gun can be divided into two: low frequency inductance gradient calculation and high frequency inductance gradient calculation. In the working engineering of rail gun, the low frequency inductance gradient can be obtained if the current is uniformly distributed in the guide rail. The simple rectangular rail is shown in figure 1.

![Figure 1. Schematic diagram of simple rectangular rails](image)

Grover[8] proposed a low frequency inductance gradient expression:

\[ L' = 0.4 I n + 1.5 + In k H + w \]  

(1)

where \( L' \) is the inductance gradient of the rectangular rail; \( H, w, s \) is the height, thickness and spacing of the rail, respectively; \( In k \) is related to the \( H, w, s \) and is obtained by looking up the table in the literature.

Kerrisk[7] proposed the expression of inductance gradient:

\[ L' = 0.4406 - 0.0777 In F_1 In F_2 \]  

(2)

In the formula,

\[ F_1 = 1 + 3.397( w / H ) - 0.06603( w / H )( s / H ) \]

\[ F_2 = 1.0077 + 2.7437( s / H ) + 0.02209( w / H ) + 0.2637( w / H )( s / H ) \]

The integral inductance gradient of the series enhanced four-rail electromagnetic launcher is composed of three parts: the self-inductance gradient of the main rail, the mutual inductance gradient between the main and secondary rails. The calculation formula of the integral inductance gradient is as follows:

\[ L' = \frac{d(L_1 + M_1 + M_2)}{dl} \]  

(3)

In the formula(3),

\[ L_1 = \sum_{i=1}^{4} L_{ii} \]  

(4)

\[ M_1 = \sum_{i=1}^{4} \sum_{j=1}^{4} M_{ij} \]  

(5)
\[ M_2 = 2 \sum_{i=1}^{4} \sum_{k=1}^{4} M'_{ik} \]  

(6)

where \( l \) represents the length of the rail; \( L' \) represents the overall inductance gradient of the launcher; \( L_i, M_i, M_{ij} \) represents the self-inductance gradient between the main rails, the mutual inductance gradient between the main rails and the mutual inductance gradient between the main and secondary rails, respectively. \( L_i \) represents the self-inductance of the \( i \) main orbit; \( M_{ij} \) represents the mutual inductance between the \( i \) main orbit and the \( j \) main orbit; and \( M_{ik} \) represents the mutual inductance between the \( i \) main orbit and the \( k \) secondary orbit.

2.2. Simulation calculation

The electromagnetic thrust drives the armature to move at high speed. The current is affected by the velocity skin effect and is concentrated to the contact surface and rail surface. In order to accurately calculate the inductance gradient of electromagnetic launcher, it is necessary to model and simulate armature and rail simultaneously. Under the principle of virtual work, it is assumed that the armature is only subjected to electromagnetic thrust in the \( y \) direction during the axial motion along the rail, and the virtual displacement is \( dy \), obtained by the law of conservation of energy:

\[ dW_z = dW_f + dW_s + dW_m \]  

(7)

Formula (7): \( W_z \) is the total energy of the system to the electromagnetic launcher; \( W_f \) is the work done by the electromagnetic thrust to the armature; \( W_s \) is the energy lost out of the field; and \( W_m \) is the increment of the magnetic field energy. Because \( dy \) is very small, it is assumed that in the instantaneous working process, the total energy launched by the system to the electromagnetic launcher is used for the electromagnetic thrust to push the armature to do work:

\[ dW_z = dW_f \]  

(8)

\[ dW_f = Fdy \]  

(9)

\[ F = \frac{1}{2} L' I^2 \]  

(10)

The formula (9) and the formula (10) are substituted into the formula (8) and simplified:

\[ L' = \frac{2dW_f}{I^2 dy} \]  

(11)

By simulation calculation, and the combined formula (11) can be used to obtain the average inductance gradient of the armature moving distance in a very short time.

3. Simulation Model and Simulation Conditions

The three-dimensional simulation model of the series enhanced four-rail electromagnetic launcher is shown in figure 2. A secondary orbit is added to the outer layer of the main orbit of the four-rail electromagnetic launcher. The relative rail current direction is the same, the secondary rail and its corresponding main rail current direction is same, main rail carries armature, the secondary rail is used to enhance magnetic field and increase electromagnetic thrust.
Figure 2. Model of series enhanced four-rail electromagnetic launcher

In the simulation model, the rail is copper material and armature is aluminum material; main rail length is 1000 mm, height is 20 mm and width is 10 mm; length, width and height of the secondary rail are consistent with main rail parameters. The distance between main and secondary rails is s = 10 mm; length of armature is 10 mm and neck thickness is 3 mm. The armature model and the face map are shown in figures 3 and 4:

Figure 3. Armature model          Figure 4. Armature elevation

The armature adopts hollow design to leave loading space for the carrier; the four drainage arcs of armature can guide and concentrate the current to achieve stronger electromagnetic thrust.

Since armature moving is a complex transient acceleration process of millisecond, eddy current solver is set up to solve the problem. When the current frequency reaches a certain value, it can simulate the of current skin effect under transient condition[11]. The current frequency is 2 kHz, the current amplitude is 50 KA and the vacuum region is 300%.

4. Influencing factors of inductance gradient

4.1. Effect of armature position on inductance gradient
To analyze the influence of different positions of armature on the inductance gradient, D = 200, 400, 500, 600, 800 mm, five positions are set up. D = 0 mm is selected as the relative zero energy position. The energy difference $\Delta E$ is obtained by comparing the energy of five different positions with the relative zero energy position, and combined formula (11) to find the average inductance gradient of the launcher when the armature is at these five positions. The record results are shown in Table 1.

Table 1. The position of the armature and inductance gradient

| $D$ / mm | 200 | 400 | 500 | 600 | 800 |
|----------|-----|-----|-----|-----|-----|
| $\Delta E / J$ | 127.84 | 253.84 | 313.34 | 369.44 | 489.79 |
| $L'/\mu\text{H}\cdot\text{m}^{-1}$ | 1.023 | 1.015 | 1.003 | 0.985 | 0.980 |

Table 1 shows that the inductance gradient decreases gradually from the tail of the rail to the exit. When the distance from the tail of the rail is 800 mm, the inductance gradient reaches 0.980 $\mu$H·m$^{-1}$, and the decrease is 4.1% compared with the 200 mm. All the simulation models take the armature distance rail tail 500 mm.

4.2. Effect of current frequency on inductance gradient
The current frequency will affect the skin depth and the inductance gradient of the launcher. In order to study the influence of different current frequencies on the inductance gradient of the launcher, five different current frequencies are selected for simulation calculation. The simulation results are shown in figure 5.
Figure 5 shows that the inductance gradient of the series enhanced four-rail electromagnetic launcher decreases with the increase of current frequency. This is because the higher the current frequency, the stronger the eddy current produced in the orbit, the more obvious the skin effect of the current, that is, the shallower the skin depth, the current almost only flows on the surface of the orbit, and the internal current of the orbit is very small. The inductance gradient of the launcher decreases. The effect of current frequency on skin depth is shown in figure 6.

![Figure 6. Distribution of current density and magnetic field intensity](image)

The current distribution diagram (left) and the magnetic induction intensity diagram (right) of the rail with current frequency of 5000 Hz and 500 Hz are given in figure 6(right). It shows that the distribution of current at the two frequencies is not uniform. When the current frequency is 5000 Hz, the current density at the inner tip of the main rail is the largest. When the current frequency is 500 Hz, the main rail current distribution is uniform and the secondary rail has current skin effect. The magnetic field distribution of the main and secondary orbit is affected by the current distribution, and the larger the current density, the larger the magnetic field can be excited in space field, so the magnetic field distribution is roughly similar to the current distribution, and the maximum magnetic induction intensity in figure (a) also appears at the inner tip of the main orbit.

4.3. Effect of main and secondary rail parameters on inductance gradient

The four main rails are used to carry armature motion, and the secondary rails is used to enhance magnetic field. Therefore, it is more practical to analyze the distance between the main and secondary rails and the geometric parameters of the secondary rails without changing the main rail parameters. The parameters of the main rail remain unchanged, the thickness of the secondary rail is \(w\), height of the secondary rail is \(h\), the spacing of the main and secondary rail is \(s\), the variation of inductance gradient with \(s, w, h\) is studied by finite element simulation.

Firstly, \(w = 10\text{mm}\), \(h = 20\text{mm}\) and the distance between the main and secondary orbits is changed to \(6\text{mm}, 8\text{mm}, 10\text{mm}, 12\text{mm}, 14\text{mm}\). The results obtained are shown in figure 7.
Figure 7. The inductance gradient varies with the spacing of the main and secondary rails

Figure 7 shows that the inductance gradient of the series enhanced four-rail electromagnetic launcher decreases with the increase of the main and secondary orbital spacing, from 1.061 \text{ uH m}^{-1} to 0.931 \text{ uH m}^{-1}, and the decrease is 12.3%. This is because the larger the distance between the main and secondary orbits, the weaker the enhancement of the magnetic field generated by the secondary orbits, resulting in the smaller the inductance gradient.

Secondly, \( s = 10 \text{ mm}, \ w = 10 \text{ mm} \) and the height of the secondary rails are 12 mm, 14 mm, 16 mm, 18 mm, 20 mm; Finally, \( s = 10 \text{ mm}, \ h = 20 \text{ mm} \), and the thickness of the secondary rails are 6 mm, 8 mm, 10 mm, 12 mm, 14 mm. The results are shown in tables 3 and 4.

Table 2. Inductance gradients at different suborbital heights

| \( h / \text{ mm} \) | 12   | 14   | 16   | 18   | 20   |
|----------------------|------|------|------|------|------|
| \( \Delta E / J \)    | 324.06 | 321.84 | 318.76 | 316.150 | 313.34 |
| \( L' / \text{ uH m}^{-1} \) | 1.037 | 1.030 | 1.020 | 1.012 | 1.003 |

Table 3. Inductance gradients under different suborbital thicknesses

| \( w / \text{ mm} \) | 6     | 8     | 10    | 12    | 14    |
|----------------------|-------|-------|-------|-------|-------|
| \( \Delta E / J \)    | 316.25 | 315.02 | 313.34 | 309.38 | 307.563 |
| \( L' / \text{ uH m}^{-1} \) | 1.012 | 1.008 | 1.003 | 0.990 | 0.984 |

Table 2 and Table 3 show that the inductance gradient of the series enhanced four-rail electromagnetic launcher decreases with the increase of the secondary rail height and thickness. This is because the height and thickness of the secondary rail increase, which leads to the increase of the cross-sectional area of the secondary rail. Under the condition of constant current, the current density on the surface of the secondary rail decreases, and the external flux decreases. The overall inductance gradient of the launcher also decreases.
5. Conclusion
In this paper, the inductance gradient of the series-enhanced four-rail electromagnetic launcher is simulated by finite element method, and the factors affecting the inductance gradient of the launcher are analyzed. The following conclusions are obtained:

(1) The inductance gradient can be calculated by the energy method, taking into account the effect of the armature on the inductance gradient of the series-enhanced four-rail electromagnetic launcher, and the farther the armature is from the tail of the rail, the smaller the inductance gradient.

(2) If the inductance gradient of the launcher is to be increased, it can be designed in the case of main and secondary rail insulation from the point of view of appropriately reducing the distance between the main and secondary rails; if the flow and mechanical bearing capacity of the secondary rail meet the requirements, the inductance gradient of the launcher can be increased by increasing the cross-sectional area of the secondary rail.

(3) When the current frequency of the load increases, the eddy current increases and the current on the surface of the rail becomes more concentrated, which causes the temperature of the rail to rise faster.

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