Simulation on temperature field of initial segment of electromagnetic rail launch

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Abstract. The temperature field analysis of electromagnetic rail launcher is an important basis for studying the launching stability and life. Aiming at the rail groove erosion phenomenon, the launching initial segment is selected as the research site. The heat generation mechanism of Joule heat and friction heat is analyzed, the heat source model is established, the three-dimensional finite element simulation model is established and the position, velocity and current waveform of the launching initial section are determined according to the circuit simulation, the finite element simulation results show that the heat in the initial stage of launching mainly concentrates on the contact surface between armature and rail. The friction heat is the main factor affecting the temperature rise of the contact surface, and the uneven distribution of the current density will lead to the uneven temperature distribution of the contact surface.

1. Introduction
Electromagnetic rail launcher is a new type of kinetic energy weapon which uses electromagnetic energy to accelerate the load to ultra-high speed. It has a broad application prospect in the military field for it can break through the limit of traditional propellant launching and achieve controllable thrust and velocity [1-3]. During the launching process, the pulsed power supply provides MA-level current in several ms, and the armature will generate thousands of times the gravitational acceleration in the strong magnetic field. Keeping good sliding contact between armature and rail is of great significance to the stability and life of the launcher under these extreme conditions [4].

Temperature is one of the important indicators for describing the contact state. The influence factors of mechanical characteristics on the contact surface between armature and rail include pretightening force during armature assembly, electromagnetic force during current conduction and thermal stress due to friction heat and Joule heat [5]. The temperature of the contact surface rises sharply due to the accumulation of heat during the launch process, which leads to significant changes in the mechanical properties of materials, such as material softening, melting, and metal oxidation, which will result in the instability of the contact state [6]. The heat accumulation makes the contact condition worse, and the stability and life of the device are significantly reduced especially under the condition of multiple continuous launches [7].

In 2002, Institution of Advanced Technology (ITA, in America) began to focus on the study of the electrical contact characteristics of armature rail and claimed that the armature transition was solved in the range of 2-3 km/s speed [3]. The problem of rail anti-ablation under discontinuous launching was solved by 2013 [8]. Due to the late start of domestic research, rail life has become one of the
difficulties restricting experimental research. In recent years, some domestic scholars have carried out some research on the thermophysical characteristics and thermal management of electromagnetic rail launcher. Lin [9] has used numerical simulation to study the transient temperature field under Joule heat source. Wang [10] has analyzed the temporal and spatial distribution of contact heat on the calculation model of contact pressure and contact resistance. Lin [11] has established a two-dimensional model of rail transient temperature for simulating degree effect and compared with experiment. But they adopted more idealized conditions and did not analyze specific experimental phenomena. Existing launching tests show that the rail edge grooves are prone to occur in the initial stage of launching. The groove pits deepen continuously with multiple launches. The most probable reason is that local high temperature causes material softening and stress concentration [3,6]. Thus in this paper, a heat source model and a three-dimensional finite element simulation model will be established to simulate the temperature field of the rail and armature in the initial stage of launching, which will provide a reference for the study of the stability and life of the electromagnetic rail launcher, and corresponding optimization methods to solve the problem of groove corrosion as well.

2. Establishment of heat source model

In the process of electromagnetic launching, the generation of heat source includes two aspects: Joule heat generated by armature current and friction heat generated by relative sliding of armature. Both of them act on armature and rail at the same time with the characteristics of time accumulation and space distribution.

2.1. Joule heat

The current, provided by pulse power supply, flows through rail and armature to form a closed circuit. Energy is consumed in the form of heat on resistance. Considering the imperfect contact condition, the resistance can be divided into resistance of armature and rail body and contact resistance [10,12]. The body resistance generates heat in the conductor while the contact resistance generates heat on the contact surface. The total resistance can be described as

$$R = R_a + R_r + 2R_c$$

(1)

where $R$ is the total resistance of armature rail; $R_a, R_r$ are the resistance of armature and rail body; $R_c$ is the contact resistance of one side between armature and rail. Contact resistance is generally composed of shrinkage resistance and film resistance. The oxide film on metal surface is destroyed during armature assembly, thus the film resistance can be neglected. Contact resistance is

$$R_c = R_s + R_b$$

(2)

$$R_s = \frac{\rho_a + \rho_r}{4na}$$

(3)

where $\rho_a, \rho_r$ are the resistivity of armature and rail materials, $n$ is the number of micro contact spots on the contact surface which can be estimated at 10 per 4 square millimetres [13], $a$ is the average radius of contact spots. The actual contact area of contact surface $A_c$ is usually much smaller than the ideal contact area, which can be derived from the following formula

$$A_c = \frac{F_c}{2H_a}$$

(4)

$$A_c = n\pi a^2$$

(5)

where $F_c$ represents the contact pressure on one side contact surface; $H_a$ is the hardness of the softer side of contact material, generally the armature material, takes the value of 150 HB; $\xi$ is the elastic
deformation correction coefficient between 0 and 1, which decreases with the increase of the contact pressure, takes 0.1. Eliminating the conductive speckle radius \( a \) which is difficult to determine, the thermal power of the contact resistance can be expressed by combining the above formulas as

\[
P_c(t) = F^2(t)R_c(t) = \frac{(\rho_a + \rho_c)}{4} \left( \frac{n_c^2 H_a}{nF_c(t)} \right)^{1/2} \cdot F^2(t)
\]

(6)

2.2. Frictional heat
Friction heat is generated on the contact surface, and the velocity of launching initial stage is small. However, due to the larger current and the larger contact pressure between armature and rail, the influence of friction heat should be considered. The frictional heat generation power on one side between armature and rail can be described as follows:

\[
P_f(t) = \mu F_c(t) v(t)
\]

(7)

where \( v \) is the relative sliding speed of armature; \( \mu \) is the sliding friction coefficient, as the movement proceeds, its value will decrease continuously.

3. Establishment of simulation model

3.1. Structural model and material parameters
According to the actual structure of the electromagnetic rail launcher, a three-dimensional finite element model is established after corresponding simplification, which is shown in figure 1. The rail is 10 mm high, 20 mm wide, 1.8 m long, 16 mm length between two rails, 2 mm high and 10 mm wide for rail bump, 25 mm long and 10 mm wide for U-type armature, and 5 mm round corner for shoulder.

![Figure 1. Finite element model of electromagnetic rail launcher.](image)

The armature material is aluminium alloy and the rail is copper alloy. Some important parameters are shown in table 1. Among them, \( \rho \) is the material density, \( \mu_r \) is the relative permeability, \( \sigma \) is the conductivity, \( k \) is the thermal conductivity and \( C_p \) is the constant pressure heat capacity.

| Table 1. Some important parameters of materials. |
|-----------------------------------------------|
| \( \rho (\text{kg/m}^3) \) | \( \mu_r \) | \( \sigma (\text{S/m}) \) | \( k (\text{W/(m·K)}) \) | \( C_p (\text{J/(kg·K)}) \) |
| armature | 2689 | 1 | 3.8×10^7 | 238 | 900 |
| rail | 8933 | 1 | 5.8×10^7 | 400 | 385 |

3.2. Circuit model
The circuit model is used to obtain a more realistic current waveform. The circuit model is shown in figure 2. Among them, pulse capacitor C1 provides current, R2 and L2 are equivalent resistance and inductance of power supply and circuit, R1 and L1 are wave-modulated resistance and inductance, and resistance R3 and inductance L3 of launcher on the right side actually show linear variation. The calculation formulas are as

\[ R_3 = R_0 + R'x(t) \]  
\[ L_3 = L_0 + L'x(t) \]

where \( R_0 \) and \( L_0 \) are the resistance and inductance of the armature rail at the initial launching position, \( R' \) and \( L' \) are the resistance gradient and the inductance gradient, \( x(t) \) is the armature displacement. The initial position of armature launching is 15 mm away from the tail of rail. The approximation is obtained by finite element analysis that \( R_0 \) is 2.25 \( \Omega \), \( L_0 \) is 8.58 \( nH \), \( R' \) is 0.15 \( m\Omega/\text{m} \), \( L' \) is 0.57 \( \mu H/\text{m} \).

\[ F_c = ma(t) = m \frac{dv(t)}{dt} = m \frac{d^2x(t)}{dt^2} = \frac{1}{2} L'I^2(t) - 2\mu F_c \]

where \( F_c \) is the resultant force in the direction of armature motion; \( a(t) \) is the armature acceleration; \( v(t) \) is the armature speed; \( \mu \) is the friction coefficient of contact area, which is constant 0.15. The contact pressure of the central rail \( F_c \) can be calculated by finite element simulation or estimated by the following formula [7]:

\[ F_c(t) = F_0 + \frac{1}{4} \alpha L'I^2(t) \cos \theta \]

where \( F_0 \) is the pre-pressure of the interference assembly, which can be regarded as constant value when the friction loss of material is neglected. According to Marshall formula of "1g/1A", \( F_0 \) is 1kN; \( \alpha \) is the coefficient of transforming electromagnetic expansion force of armature arm into electromagnetic extrusion force, taken as 0.5; \( \cos \theta \) is the cosine of the angle between armature tail wing and rail, taken as 0.956.

Assuming that the rail is infinitely long and the maximum time is 5 ms for transient circuit analysis, the circuit waveform curve, armature velocity curve and displacement curve can be obtained. As is shown in figures 3-5, the current reaches a peak value of 200 kA at 0.23 ms. This paper sets the armature to move 1.65 m before leaving the guide rail. The exit time of the armature is about 1.68 ms,
and the exit speed is about 1733 m/s.

![Figure 3. Current waveform.](image)

![Figure 4. Armature velocity curve.](image)

![Figure 5. Armature displacement curve.](image)

3.3. **Initial segment simulation model**

It can be seen from the experimental phenomena of rail groove corrosion in the initial stage of launch that most of the groove corrosion occurs in the time and position where the loading current is large and the contact time is long [4,6]. In this paper, the position of armature, about two armature lengths (51 mm), is selected as the fixed research position. The time is 0.35 ms, the speed is 409 m/s and the current position is in the descending edge, reaching 192 kA.

Considering the skin effect of current, the armature is fixed, the Joule heat source of contact resistance and the friction heat source are generated at the interface of contact surface. The heat source added to the contact surface is taken as a constant. The contact resistance calculated by the above formula is about $3.313 \mu \Omega$ respectively, and the peak heat generating power is $1.325 \times 10^5$ W and $2.285 \times 10^5$ W. Using transient electromagnetic-thermal coupling simulation, considering the worst heat generation, the model is set as heat insulation, the ambient temperature is 20℃, and the total time is 0.35 ms. The current density and temperature field distribution on armature and rail are investigated.

4. Simulation results and analysis

4.1. **Current density**

Current density is an important factor to measure Joule heat. In the simulation, different sections are selected to investigate the current density at different time, as shown in figures 6 and 7.

![Figure 6. Current density diagram of side section. (a) 0.025 ms, (b) 0.1 ms, (c) 0.225 ms and (d) 0.35 ms.](image)
From the cross section of figure 6, it can be seen that the skin effect is obvious at the moment of 0.025 ms when the current is just passed in. The maximum current density is located at the neck of the armature, followed by the junction between the armature tail and the rail, and the current in the rail is concentrated in the convex platform. With the passage of time, the current gradually permeates into the material. The current density near the peak time of current curve (0.225 ms) reaches $5.663 \times 10^9$ A/m$^2$, but the maximum current density appears before the peak time of current current, reaching $5.998 \times 10^9$ A/m$^2$.

From the longitudinal section of figure 7, it can be seen that the current initially gathers at the center of edge sides of the armature, and then diffuses to the whole section. The current on the contact surface gathers at the end of armature at edge sides, where the heat generating power is high and the material is easy to soften due to local high temperature, which is close to the groove location of armature and rail in the experiments.

4.2. Temperature distribution
The location and diffusion path of temperature can be visually understood by temperature distribution map. After 0.35 ms, the temperature distribution of armature and rails ,investigated by transient thermal simulation method, is shown in figures 8 and 9.
As shown in figure 8, the highest temperature of the armature appears on the contact surface. In the initial stage of launch, contact heat (including contact resistance Joule heat and friction heat) is generated rapidly on the contact surface. Due to the limited heat transfer capacity of materials in a short time, the instantaneous high temperature on the contact surface reaches 670℃, which exceeds the melting point of armature material. This is consistent with the aluminum layer detected on the inner surface of rail in experiments. Because of the skin effect of the current, the temperature of the tail and side edges of the armature on the contact surface is slightly higher than that of other parts. In addition, the temperature concentration occurs at the inner corner of the armature neck, which corresponds to the current density concentration in the upper text.

Because of the armature movement, the rail thermal contact area is larger during the process of launch. The actual temperature value of the rail should be lower than that of the simulation, but the distribution is similar. As can be seen from figure 9, the heat generation of the rail is concentrated in the thin layer on the surface of the convex platform, and thermal diffusion occurs both in the axial and radial direction of the launch. When the Joule heat source of electromagnetic field is coupled into the thermal field, the inconsistent finite element meshing results in abnormal temperature in small number of units, but does not affect the overall solution.

4.3. Optimization analysis
From the point of view of heat generation, Joule heat plays an important role both inside and on the contact surface between armature and rail, but the friction heat on the contact surface of armature rail is more significant at the initial stage of launch. Local high temperature on the contact surface aggravates the stress concentration, which leads to groove corrosion on the rail. When the armature melts locally, the electrical contact performance decreases, which will aggravate the groove corrosion on the rail. Through the simulation analysis in this paper, the following aspects can be considered to reduce the thermal effect in the initial stage of launch:

- Material aspect: adopting armature material with high melting point, rail material with high strength and lubricant with good heat transfer performance on the contact surface.
- Structural aspects: carrying out fillet treatment at the end of armature tail fin, changing the section shape of contact surface (concave or convex) and reasonably controlling the armature interference.
- Cooling passage can be set in the rail to accelerate heat conduction.

5. Conclusion
In this paper, the launching initial section is selected as the research site for the rail groove erosion phenomenon. The heat generation mechanism of Joule heat and friction heat is analyzed, the corresponding heat source model is established, and the three-dimensional finite element simulation
model based on circuit simulation is established. The main conclusions are as follows:

- In the initial stage of launch, the heat is concentrated on the contact surface, and the heat transfer effect in the conductor is not obvious.
- Under hundreds of kA peak current loading, friction heat is the main factor that causes the temperature rise of the contact surface at the initial stage of launch, which is also the basic cause of groove corrosion.
- The uneven distribution of current density will lead to uneven temperature distribution on the contact surface, accelerating the formation of groove pits on edge of contact surface.

In order to obtain more reliable conclusions, the follow-up study will start from the coupling of force field on the contact surface. The non-uniform distribution of contact force makes the current and heat more concentrated, especially at the edge of the contact area.

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