

Kinematic Characterization of Electromagnetic Energy Propulsion Device Considering Dynamic Conductivity

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Conductivity has an effect on the inductance gradient, which change the magnitude of electromagnetic force. An electromagnetic-thermal coupling finite element model considering dynamic conductivity for electromagnetic energy equipment propulsion devices is proposed to investigate the effect of conductivity on the armature motion characteristics. By taking the rail current obtained from the experiment as the input parameter, the sequential coupling method is adopted to calculate the dynamic electromagnetic force during the launching process. Thus, the change of conductivity and armature speed under the consideration of high-speed movement of armature is obtained. The accuracy of the proposed model is verified by comparing the experimental data with the simulation data results. The work in this paper provides theoretical support and valuable reference for further reliability prediction and optimal design of electromagnetic propulsion devices.

Index Terms—Dynamic conductivity, electromagnetic propulsion device, multiphysics field coupling.

I. INTRODUCTION

An electromagnetic energy equipment propulsion device is a new type of launcher that uses electromagnetic force to push the armature to move at high speed in the chamber. The inductance gradient is one of the important parameters of the electromagnetic energy equipment propulsion device, which directly affects the magnitude of the electromagnetic thrust of the armature. The current distribution in the rail is an important factor affecting the inductance gradient. While the structure of the propulsion device, the shape of the rail cross-section, geometric dimensions, rail spacing and material properties and other factors will affect the distribution of the current density. The rail conductivity change will also have a direct impact on the rail current density, which further affects the size of the inductance gradient. Therefore, the calculation of rail dynamic conductivity is of great significance for the design of the propulsion device structure and the prediction of the motion behavior of the armature.

The current research on the dynamic change of conductivity for electromagnetic propulsion devices dynamic motion characteristics is less. This paper through the consideration of electromagnetic energy equipment propulsion device inside the conductivity dynamic change factors, the establishment of device internal parameter dynamic change of multi-physics field coupling simulation model. Through the electromagnetic-thermal multi-physical field coupling process, the dynamic electromagnetic force in the launching process is obtained by calculation, and the armature muzzle velocity is used as the output result and verification parameter to verify the accuracy of the multi-physical field simulation model considering the dynamic conductivity of the rail, and the new model is able to more accurately predict the change of the armature launching velocity.

II. A COUPLED MULTIPHYSICS FIELD MODEL CONSIDERING DYNAMIC CONDUCTIVITY

The motion characteristics of a linear electromagnetic energy propulsion device depend directly on the track inductance gradient L' . The inductance gradient for the track is the amount of inductance per unit track length, the electromagnetic force on the railgun armature is:

$$F_{em} = 0.5LI'^2 \quad (1)$$

The dynamic behavior of the armature during acceleration is affected by a combination of electromagnetic and frictional forces. Its equation of motion is expressed as:

$$ma = F_{em} - F_f \quad (2)$$

where m and a are the mass and acceleration of the armature, respectively; F_{em} and F_f are the electromagnetic and frictional forces on the armature, respectively. Establish the numerical calculation model of the electromagnetic propulsion device. The electromagnetic field is modeled by the magnetic diffusion equation based on the consideration of the effect of armature motion:

$$\begin{cases} \nabla \cdot \left(-\sigma \nabla - \sigma \frac{\partial A}{\partial t} + \sigma v \times \nabla \times A \right) = 0 \\ \nabla \times \left(\frac{1}{\mu} \nabla \times A \right) + \sigma \nabla \phi + \sigma v \times \nabla \times A = 0 \end{cases} \quad (3)$$

where ∇ is the Hamiltonian operator; A is the magnetic vector potential; ϕ is the electric scalar potential; μ is the magnetic permeability of the conductor; σ is the electric conductivity; and v is the velocity. The rail heat transfer equation is:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \cdot \nabla T) + Q_{j1} + Q_{j2} + Q_f \quad (4)$$

where T is the temperature, ρ is the mass density, C_p is the specific heat capacity, k is the thermal conductivity, Q_{j1} is the Joule heat of the current obtained from the electromagnetic-temperature coupling, Q_{j2} is the heat of the contact resistance generated between the contact surfaces of the pivot rail, and Q_f is the heat of friction generated in the process of sliding friction. The structural field control equations are:

$$\begin{cases} \rho J = \rho_0 \\ \sigma_{ij,i} + \rho f_i = \rho a_i \\ \rho w^{\text{int}} = D_{ij} \sigma_{ij} \end{cases} \quad (5)$$

where: ρ_0 is the initial density of the material; J is the Jacobi matrix; σ_{ij} is the Cauchy stress tensor; $\sigma_{ij,i}$ is the skewness of the Cauchy stress tensor with respect to x_i ; f_i is the volumetric force density; a_i is the acceleration; w^{int} is the internal energy per unit mass; and D_{ij} is the strain rate tensor. The rail current curves obtained from measurements with the experimental setup are shown in Fig. 1:

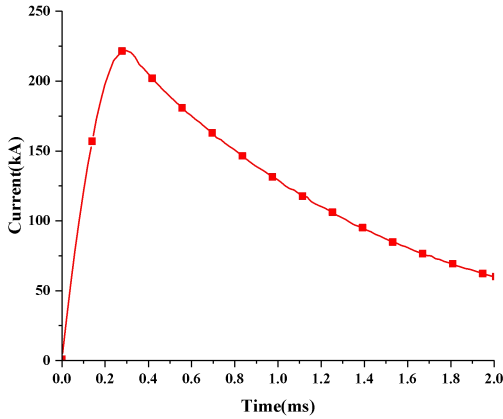


Fig. 1 Current-time curve.

The flow chart of the multi-physics field coupling model of the linear electromagnetic energy propulsion device is shown in Fig. 2:

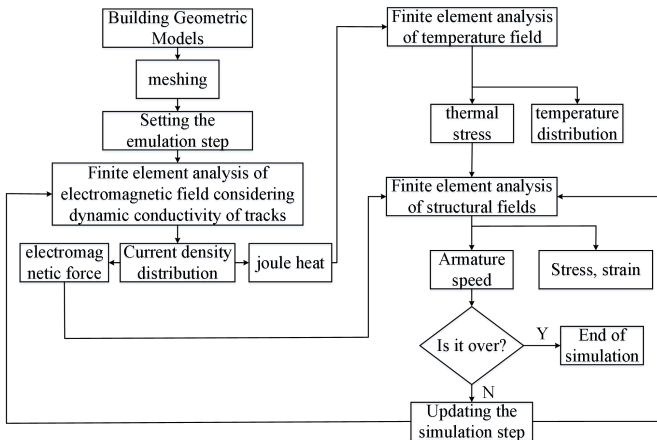


Fig. 2 Flowchart of multi-physical field coupling.

III. CALCULATION RESULTS

Rail conductivity shows a trend of decreasing and then recovering with time, and the current density distribution at 0.6ms is calculated for the electromagnetic energy equipment propulsion device model considering the dynamic conductivity and compared with that of the electromagnetic energy equipment propulsion device model with the static conductivity, and the smaller rail conductivity will result in the enhancement of the rail magnetic field diffusion, the non-uniformity of the current distribution, and the rail current density will become larger and reduce the rail inductance gradient, which will lead to the electromagnetic thrust being lower than that of the constant rail conductivity. As a result, the electromagnetic thrust is lower than that at constant rail conductivity, as shown in Fig. 3:

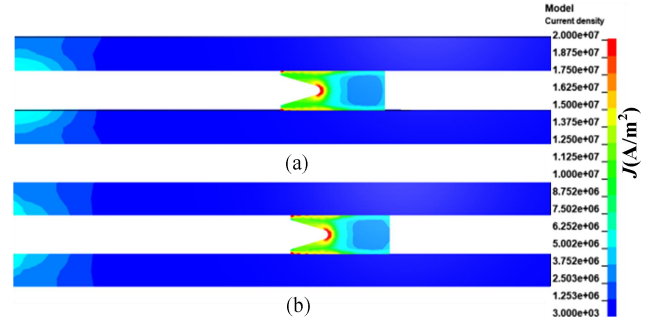


Fig. 3 Current density distribution (a) static conductivity case. (b) dynamic conductivity case.

The comparison of armature velocity in different cases is shown in Fig. 4:

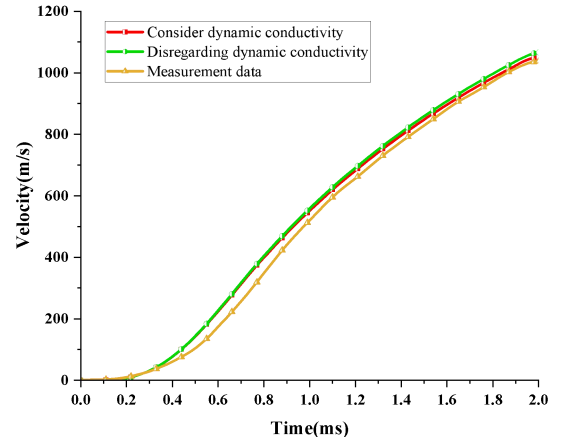


Fig. 4 Comparison of armature velocity in different cases.

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