

Prediction Method for Magnetic Field in the Armature-Rail System of Electromagnetic Propulsion Device

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In electromagnetic propulsion devices, the armature experiences significant aerodynamic heating during its ultra-high-speed motion, resulting in a substantial rise in surface temperature, which in turn affects its electrical conductivity, structural strength, and overall motion characteristics. Particularly, in structural designs where insulating support materials are configured on both sides of the armature, local flow field disturbances and heat accumulation become more pronounced, further exacerbating the aerodynamic heating issue. To accurately characterize the armature's response under aerodynamic thermal loading, this paper first establishes an integrated fluid-solid-thermal coupled numerical model encompassing the armature and air. Transient simulations are conducted to capture the evolution of the thermomechanical characteristics of the armature during its high-speed motion within the barrel. Subsequently, the temperature field obtained from the fluid, solid and thermal coupled simulation is incorporated into temperature-dependent models of the armature bulk resistance and armature-rail contact resistance. By dynamically updating the material resistivity and contact state parameters, a time-varying resistance model under thermo-electrical coupling conditions is developed. Based on this model, a time-domain analytical computation of the muzzle voltage is performed. Finally, by comparing the muzzle voltage results with and without considering aerodynamic thermal loading against experimental measurements, the reasonableness and validity of the proposed aerodynamic heating model are verified.

Index Terms—Electromagnetic propulsion device, pneumatic thermal loading, fluid, solid and thermal coupling, thermal and force characteristics.

I. INTRODUCTION

THE rail-type electromagnetic propulsion devices have attracted significant attention due to their advantages of high acceleration, fast response, and compact structure. As the core operating component of such devices, the armature moves at ultra-high speeds along the rails under strong pulsed electromagnetic forces, and its performance directly determines the energy conversion efficiency and operational stability of the system [1],[2].

With the continuous increase in motion speed, strong interactions between the armature and the surrounding air occur, leading to the formation of high-temperature shock waves and boundary-layer thermal coupling effects. The rapid rise in the armature surface temperature can not only cause material softening and structural deformation but also alter its electrical conductivity and contact conditions, potentially leading to motion instability or functional failure in severe cases [3]. Notably, in practical engineering applications, insulating support materials are often configured on both sides of the armature to achieve electromagnetic insulation and structural positioning. The interaction between these non-conductive structures and the high-speed flow field induces local flow disturbances and thermal flux concentrations, further intensifying the thermal load and non-uniform heat transfer on the armature surface, thereby enhancing the impact of aerodynamic thermal coupling effects on system performance.

Existing studies have primarily focused on electromagnetic force optimization and structural response analysis within electromagnetic propulsion systems, while systematic modeling and thermomechanical evaluation of aerodynamic

heating effects on ultra-high-speed armatures remain limited. Therefore, this study first establishes an integrated fluid, solid, and thermal coupled numerical model encompassing the armature, air domain, and insulation structures, systematically analyzing the evolution of the temperature field and the characteristics of the thermal stress response under aerodynamic thermal loading conditions. On this basis, an electrical simulation model of the electromagnetic propulsion device is constructed by incorporating the effects of temperature on the bulk resistance of the armature and the armature-rail contact resistance. By comparing the muzzle voltage results obtained with and without considering aerodynamic thermal loading against experimental measurements, the reasonableness and validity of the proposed aerodynamic heating model are verified. The findings of this study can provide theoretical foundations and numerical support for thermal protection design, thermo-electrical performance evaluation, and motion response prediction of armatures in electromagnetic propulsion devices.

II. THERMAL AND FORCE CHARACTERIZATION OF ARMATURE UNDER PNEUMATIC LOADING

During the launch process of an electromagnetic railgun, the armature travels at hypersonic speeds within a narrow barrel channel, forming a highly compressed boundary layer flow between its surface and the surrounding air. Due to the confined compression of the gas inside the barrel and the viscous effects at the armature wall, intense temperature gradients develop within the boundary layer, leading to significant heating of the gas near the armature's leading edge and surface. The high-temperature air transfers heat to the lower-temperature armature

wall through convective heat transfer, inducing strong aerodynamic heating effects. In the fluid domain, the conservation behaviors of mass, momentum, and energy for the high-speed airflow are governed by the compressible form of the Navier–Stokes equations, extended from their incompressible formulation. The governing equations are expressed as follows:

$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \\ \frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} \\ \frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\mathbf{v} (\rho E + p)) = \nabla \cdot (k \nabla T) + \Phi \end{cases} \quad (1)$$

Where ρ is the fluid density. $\mathbf{v}$ is the velocity vector. p represents the pressure acting on the fluid element. $\boldsymbol{\tau}$ is the viscous stress tensor. E is the total energy comprising internal energy and kinetic energy. k denotes the thermal conductivity of the fluid. T is the temperature. and Φ represents the viscous dissipation term. In the armature solid domain, the thermal behavior satisfies the heat conduction governing equation for thermoelastic materials, which can be expressed as:

$$\rho_s c_p \frac{\partial T}{\partial t} = \nabla \cdot (k_s \nabla T) + Q \quad (2)$$

where, ρ_s , c_p , k_s are the density, specific heat capacity, and thermal conductivity of the armature material, respectively. Q is the internal heat source intensity. The mesh discretization result of the fundamental model is shown in Fig. 1. The calculated temperature field distribution and pressure field distribution of the armature at velocities of 1000 m/s and 1500 m/s are shown in Fig. 2. and Fig. 3.

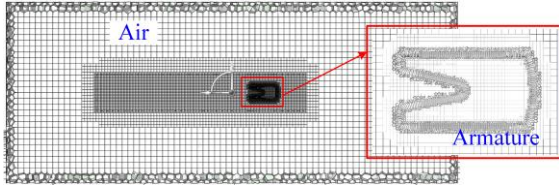


Fig. 1. The mesh discretization result of the fundamental model.

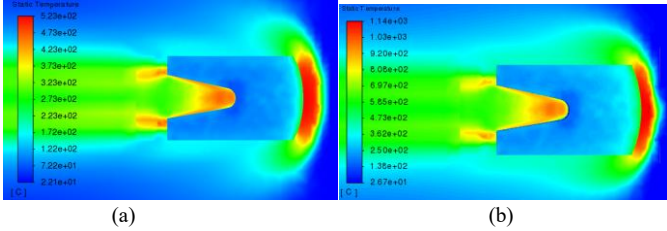


Fig. 2. Temperature distribution. (a) 1000 m/s. (b) 1500 m/s.

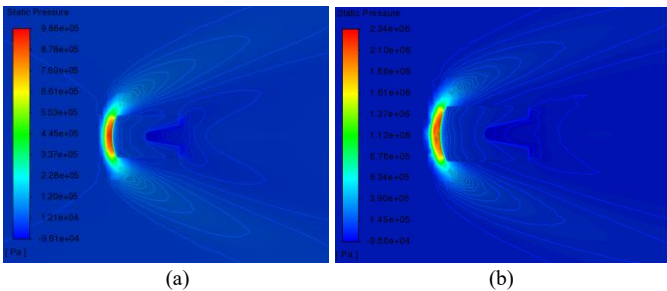


Fig. 3. Pressure distribution. (a) 1000 m/s. (b) 1500 m/s.

III. SYSTEM SIMULATION AND EXPERIMENTATION

The main factors causing the change in the muzzle voltage

$U(t)$ are the induced voltage $E(t)$ during armature movement, the contact resistance $R_c(t)$ voltage drop on the contact surface of the armature-rail, and the armature bulk resistance $R_a(t)$ voltage drop.

$$U(t) = I(t)R_c(t) + I(t)R_a(t) + E(t)$$

The contact surface conductivity h_c is calculated based on the CooperMikic-Yovanovich (CMY) relationship.

$$h_c = 1.25 \frac{\rho_r(T) \rho_a(T)}{\rho_r(T) + \rho_a(T)} \frac{m}{h} \left(\frac{P}{H} \right)^{0.95}$$

Where m is the average slope of the rough surface. h is the average height of the rough surface. P is the contact pressure. H is the surface hardness of the softer material. $\rho_a(T)$, $\rho_r(T)$ are the temperature-dependent armature and rail conductivity. During armature motion, the main sources of heat in the armature-rail system include the resistive Joule heat generated when the current passes through the armature rails and the frictional heat generated by the high-speed sliding between the armature rails. The armature body conductivity and contact resistance conductivity vary with temperature. The conductivity is further changed under the loading of aerodynamic thermal conditions, so the electrical simulation model of the electromagnetic propulsion device shown in Fig. 4 is constructed based on the measured armature speed and rail current. The calculated rifling voltages with and without aerodynamic thermal conditions are plotted against the measured values as shown in Fig. 5.

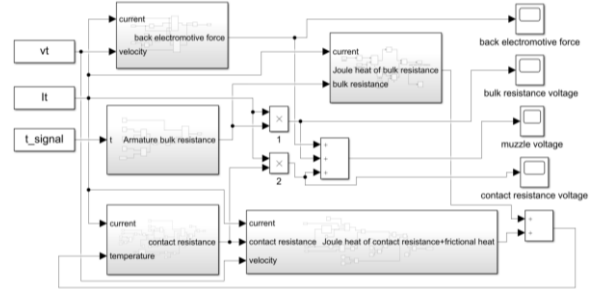


Fig. 4. Electromagnetic propulsion drive electrical simulation diagram.

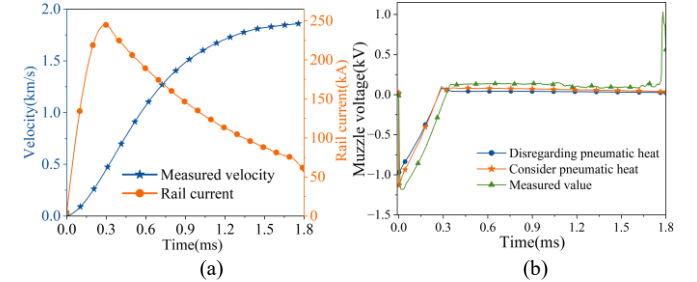


Fig. 5. (a) The measured armature velocity and rail current. (b) Comparison chart of muzzle voltage.

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