

Research on the Armature Motion Characteristics of Electromagnetic Propulsion Device

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In electromagnetic propulsion devices (EPD), the equivalent armature conductivity varies dynamically with bulk conductivity and contact resistance, which directly affects the motion characteristics of devices. However, under extreme electromagnetic, thermal, and force shock conditions, real-time in-situ measurement of armature conductivity remains challenging. To improve the computational accuracy of numerical models, this paper proposes a method for analyzing the motion characteristics of EPD based on dynamic armature conductivity inversion. First, the real-time velocity of the armature and the spatial magnetic field at the measurement points are obtained through electromagnetic propulsion experiments. The spatial magnetic field calculated from finite element models considering different armature conductivities is parameterized by a Deep Neural Network (DNN). Then, an inverse model for armature equivalent conductivity is established using the Gradient Descent method (GD). The computed values from the parameterized finite element model are corrected in real time using the measured magnetic flux density at the measurement points to obtain its spatio-temporal characteristics. Secondly, the transient electromagnetic-thermal-mechanical coupling model of armature-rail is established to analyze the influence of dynamic armature conductivity on the motion. Finally, experiments confirm that considering dynamic armature conductivity significantly improves the computational accuracy of the finite element model. This method provides theoretical guidance for reliability prediction and structural optimization of electromagnetic energy device and offers innovative solutions for real-time in-situ measurement of material properties under extreme conditions.

Index Terms—Dynamic armature conductivity, electromagnetic propulsion device, motion characteristics, parametric inversion.

I. INTRODUCTION

IN THE modern applications of electromagnetic dynamics, electromagnetic propulsion device has attracted significant attention due to its ability to rapidly and efficiently convert electromagnetic energy into mechanical kinetic energy [1]-[2]. The motion characteristics of the armature are crucial to launch performance, as they determine the energy conversion efficiency of the armature-rail system and influence the overall stability and reliability of the device. The working process of electromagnetic propulsion device is excited by high-power pulsed current, resulting in extremely high exit speeds and drastic changes in the electromagnetic and thermal properties of the armature-rail material [3]-[4]. Therefore, actual service conditions must be considered when analyzing the comprehensive electromagnetic performance of the device. The armature conductivity dynamically changes due to variations in its intrinsic conductivity and contact conductivity, impacting the current distribution characteristics and, consequently, its motion behavior. Real-time, in-situ measurement of armature conductivity under the extreme conditions of high-speed motion is extremely challenging.

Currently, traditional modeling largely overlooks the dynamic conductivity of the armature and its impact on the motion characteristics of electromagnetic propulsion drive. Most studies addressing the impact of armature conductivity on kinematic characteristics either assume a fixed conductivity or only consider the temperature effect under static conditions, failing to accurately represent the armature's motion behavior under actual working conditions. Therefore, this paper proposes a method to analyze the motion characteristics of

electromagnetic propulsion devices based on dynamic armature conductivity inversion.

II. PARAMETER MEASUREMENT

To accurately measure key parameters during armature movement, an experimental test platform of the electromagnetic propulsion device is constructed, as shown in Fig. 1. The real-time velocity of the armature and local spatial magnetic field data are obtained by measuring the induced voltage generated by the magnetic field along the armature's movement direction using a custom-built B probe placed in the insulating outer layer. The measurement results are shown in Fig. 2.

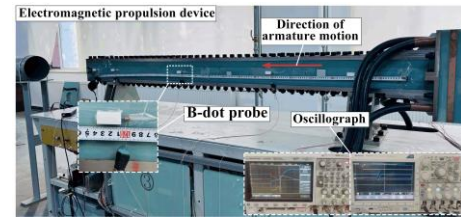


Fig. 1. Parameter measurement experiment platform.

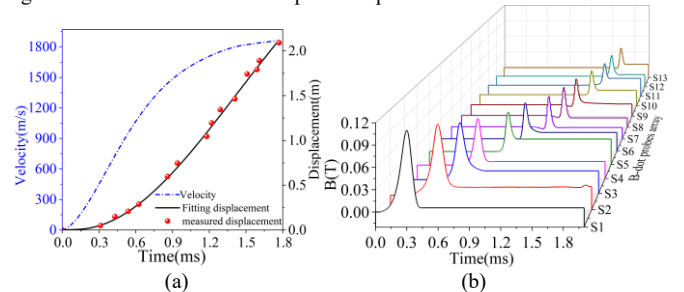


Fig. 2. The measurement results. (a) Displacement and velocity curves

with time. (b) The magnetic flux density at the position of the B-dot probes.

The armature displacement and velocity curves with time are derived by fitting the zero-crossing moments and positions of the signals from each B-dot probe. The induced voltage measured at each b-dot probe is calculated based on the magnetic flux density at the probe's position using Faraday's Law of Electromagnetic Induction.

III. PARTIAL RESULTS BASED ON ARMATURE CONDUCTIVITY INVERSION

By applying the frequency sweeping method, the electromagnetic solution equation for the armature rail, accounting for the velocity skin effect, is formulated as:

$$\begin{cases} \nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} + \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla \varphi \right) = \mathbf{J}_s \\ \nabla \cdot \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla \varphi \right) = 0 \end{cases} \quad (1)$$

where, μ and σ are the material magnetic permeability and electrical conductivity, respectively. $\mathbf{A}$ and φ are the magnetic vector potential and scalar potential. $\mathbf{J}_s$ is the current density. The calculated magnetic flux density distribution of the armature at the 30 cm position on the rail is shown in Fig. 4.

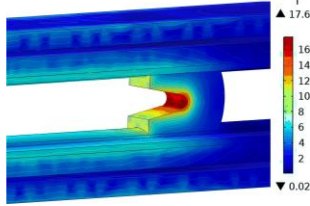


Fig. 3. Magnetic flux density distribution.

By combining DNN with the above the finite element model, an efficiently parameterized model is constructed to realize the fast mapping of the input armature conductivity to the output flux density of the measurement points, and it is applied to the inverse model of dynamic armature conductivity. Fig. 10 shows the comparison between the predicted values from the DNN parameterized model and the simulated values from the finite element model for magnetic flux density at the measured points on the test set with an armature conductivity of 24 (MS/m).

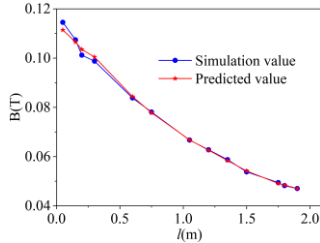


Fig. 4. Magnetic flux density at the armature conductivity of 24 S/m.

The armature conductivity inversion is achieved by minimizing the difference between the magnetic flux density at the measurement points calculated by the parameterized model and the measured magnetic flux density. The objective function is:

$$\begin{cases} \psi(\sigma_l) = \frac{1}{N} \sum_{l=1}^N (B_c^l(\sigma_l) - B_m^l)^2 \\ \text{s.t.} \quad 0 \leq \sigma_l \leq 50 \end{cases} \quad (2)$$

where, σ_l is the conductivity of the armature at displacement l . $B_c^l(\sigma_l)$ and B_m^l are the flux density calculated by the parameterized model and the measured flux density, respectively. The inversion flow of dynamic armature conductivity integrated with DNN and DGD is shown in Fig. 5.

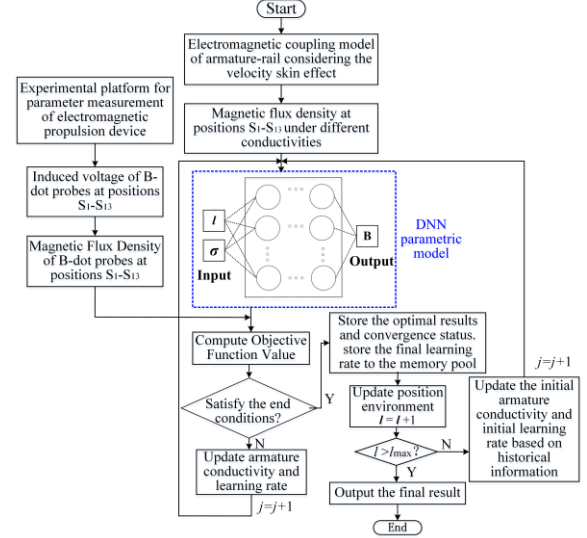


Fig. 5. Parameter inversion flowchart.

The comparison curves of the corrected flux densities at different locations with the measured values are obtained. The curve of armature equivalent conductivity with armature displacement l , calculated from the inverse model. The inversion results are shown in Fig. 6.

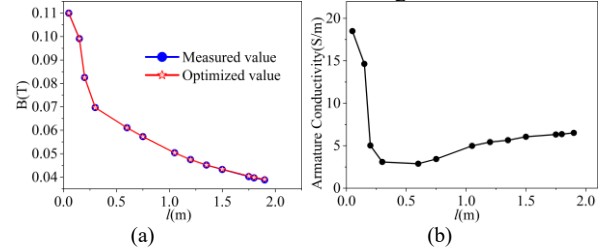


Fig. 6. The inversion results. (a) Comparison of the optimized magnetic flux density with the measured values. (b) The curve of armature equivalent conductivity with l .

Based on the dynamic armature conductivity obtained by the above inversion, the electromagnetic, thermal, and mechanical coupling model of armature-rail is established. And the armature motion characteristics is analyzed by the finite element method.

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