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Research on proximity effect of electromagnetic railgun

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Abstract

The rails of electromagnetic railgun can be ablated by the temperature rise due to current concentration. The current distributions on the rails and armature are not only affected by the skin effect, but also influenced by the proximity effect which is rarely mentioned. This paper illustrated the difference between skin effect and proximity effect, and the influencing factors of proximity effect were investigated. Results show that the current is concentrated on the surface around rails due to the skin effect, and the proximity effect exacerbates the current density on the inner surfaces of rails. Decrease in distance from rails enhances the proximity effect, but has nothing to do with the skin effect, which also augments the rail resistance, resulting in temperature rise. It can explain the reason why the ablation is often detected in the small caliber railgun. Research results in this paper can provide support for design and optimization of electromagnetic railgun.

Keywords: Electromagnetic railgun; Proximity effect; Skin effect; Ablation

1. Introduction

The electromagnetic railgun (EMG) is composed of rails, armature, insulators and containment [1–3]. The armature can be sped up to 2 km/s by feeding the exciting current to the breech of railgun [4,5]. However, ablation occurs frequently on the rails during experiments. Researches show that one important reason of this phenomenon is temperature rise due to current crowding [6–8]. The current distributions on rails and armature are not only affected by the skin effect, but also influenced by the proximity effect which is rarely mentioned. Both the effects play important roles in the EMG performance and behavior.

In this paper, the difference between skin effect and proximity effect were discussed. The distribution of current density on rails was calculated in three cases. The first case is for a single rail powered by a sinusoidal current pulse and only influenced by the skin effect. The second case is for two adjacent rails, only left one is powered by sinusoidal current pulse. The third case is for two adjacent rails all powered by sinusoidal current pulse with opposite directions. In last two cases, the skin effect and proximity effect are both considered.

The proximity effect is not only affected by frequency like the skin effect, but also affected by the distance between rails. The current distribution due to proximity effect alters the internal impedance of rails, and influences the EMG launch efficiency finally. It is significant and important to study the impact of proximity effect on electromagnetic railgun.

2. Formulations

The time-varying magnetic field generated by the time-varying current induces the eddy current on the rails. It makes the current distribution toward the periphery of rails. This phenomenon can also be caused by a nearby rail, which is denoted as “proximity effect” [9,10].

The modifications on the internal resistance and inductance due to proximity effect are not easily described by means of analytical formula. We have used a FEM code in the frequency domain to evaluate the EM field of copper rails. Ansoft computer program was employed for calculation. The vector potential, current density, and magnetic field were evaluated by Ansoft for each node of mesh.

The quantities are calculated by the following formulas

$$\nabla\times\frac{1}{\mu}(\nabla\times A)=(-\nabla\varphi-j\omega A)(\sigma+j\omega\varepsilon) \quad (1)$$

$$I_{\mathrm{T}}=\int_{\Omega}J\mathrm{d}\Omega=\int_{\Omega}(-\nabla\varphi-j\omega A)(\sigma+j\omega\varepsilon)\mathrm{d}\Omega \quad (2)$$

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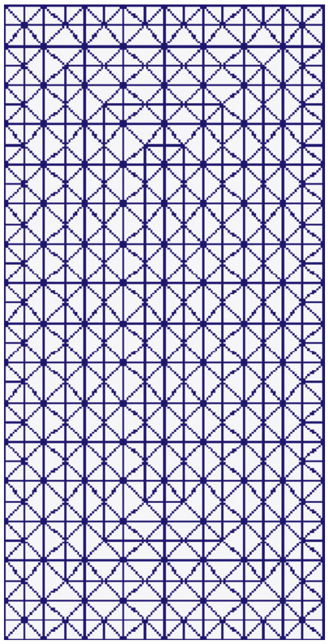


Fig. 1. 2D model and mesh of rail.

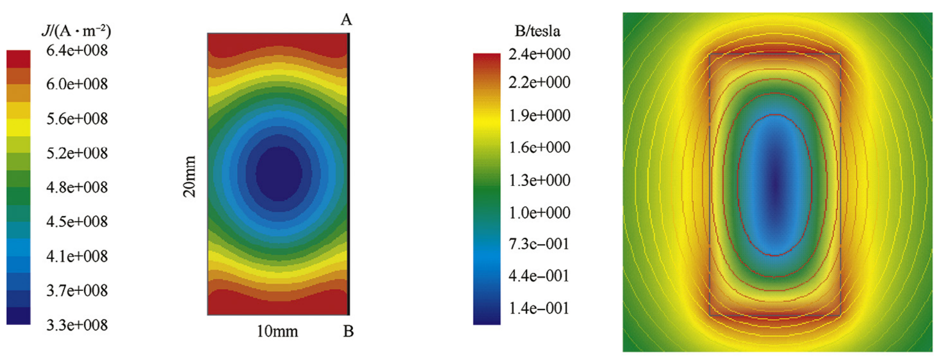
where μ is the relative permeability; A is the vector magnetic potential; φ is the scalar potential; ω is the angular frequency; σ is the conductivity; ε is the dielectric constant; I_T is the total exciting current; and J is the current density.

The A-φ method is employed to solve the wave Eqs. (1) and (2). By obtaining the vector magnetic potential A and scalar potential φ of each node, the internal resistance R and inductance L can be solved by the following formulas

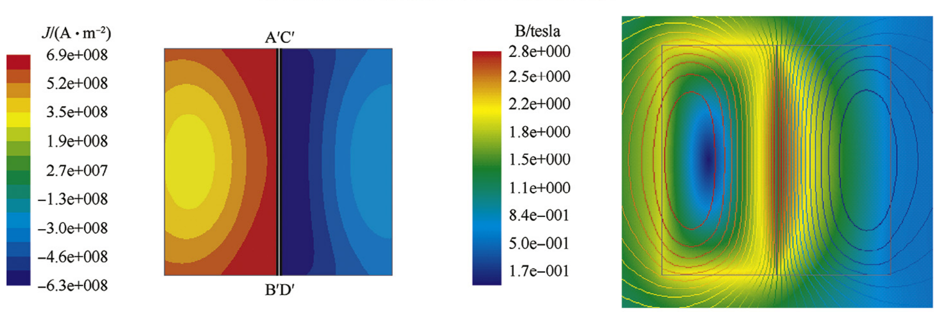
$$R = \frac{1}{\sigma I_{peak}^2} \int_V |J|^2 \, dV \tag{3}$$

$$L = \frac{1}{I_{peak}^2} \int_V \mu |H|^2 \, dV \tag{4}$$

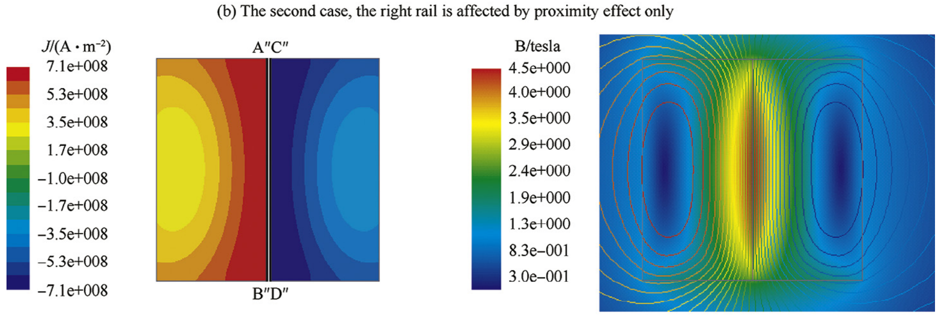
where I_{peak} is the peak amplitude of harmonic current; V is the volume of conductor; and H is the magnetic field intensity. In the program of Ansoft, the default length of a 2D model is 1m. Thus, the values of resistance gradient R' and inductance gradient L' are equal to R and L, respectively.



(a) The first case, which is affected by skin effect only



(b) The second case, the right rail is affected by proximity effect only



(c) The third case, both rails are affected by skin effect and proximity effect

Fig. 2. Current distribution and magnetic field at 100 kA and 200 Hz.