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ANALYSIS OF INDUCTANCE GRADIENT AND CURRENT DENSITY IN A LAMINATED AND BEVELED RAILGUN FOR BEST PERFORMANCE

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Abstract- Inductance gradient is one of the most important parameters in designing and manufacturing of railguns. A better performance can be achieved as the inductance gradient increases. In this paper a railgun with laminated and beveled rails is proposed to improve the inductance gradient. Then, it is applied on a typical railgun by using a 3-D Finite Element (FE) simulation. According to the FE analysis results, although it introduces a notable increase on the inductance gradient but it deteriorates the distribution of the current density in the armature. This problem is also solved by using laminated armature. The validity of the proposed method is verified by simulation.

Keywords: Inductance Gradient, Current Density, Beveled Rail, Laminated Armature.

I. INTRODUCTION

Nowadays, due to the acceleration of technological and scientific advances, scientist required to design and use advanced technological application in technology and electro mechanism [1]. Some special equipment used for special applications. But to better performance need to more specialized study on it. One of this exceptional equipment that gets a lot of attention today is railgun. It is a launcher that can be used for different applications. The device uses electromagnetic force to launch. The force on the projectile and consequently the muzzle speed in a railgun increases with inductance gradient. Therefore, the attempt to maximize this parameter is one of the main goals in the design and manufacturing of railguns. The simplest form of force equation on the projectile in a railgun can be written as:

$$F_{proj} = \frac{1}{2} L' I_r^{\,2} \tag{1}$$

where, L' is the inductance gradient the rail/armature combination along the rails, I_r is the driving current, and F_{proj} is the armature and projectile force.

This equation is obtained from the virtual work method which is based on the conservation of energy. It is extracted by partially differentiating of the stored energy in the magnetic field, and also assuming that the entire developed mechanical energy is delivered to the projectile. In practice some of the magnetic energy is converted into strain energy in the structure and it is not taken into account in the simplest form of force Equation (1). In addition, it assumes a steady current distribution in the rails, independent of the projectile position and movement. Some limitations of (1) are described in [6].

Eddy currents are practically generated in different parts of current carrying parts of the rails as a result of the movement of the projectile and the diffusion of the magnetic field which results in a drag force exerted on the projectile [8]. Eddy currents are mostly located in the rails near the contact [3].

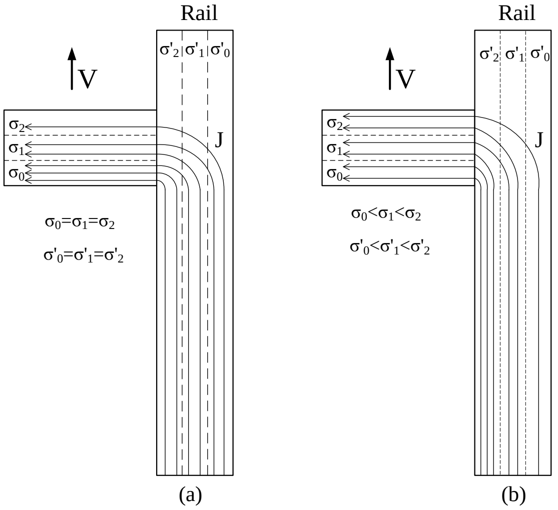
By providing the magnetic fields and currents at the armature, the inductance gradient L' can be calculated and then the mechanical forces in the railgun and its electrical performance with reasonable accuracy can be predicted. This information allows the railgun designers. To perform relatively rapid tradeoff assessments for proposed launcher designs. One of the main objectives to give a precise computation of the inductance gradient is geometric parameters of the railgun.

In some cases, the number of rails is increased in order to increase the inductance gradient [4, 5]. However, the complication of the system and also the mechanical stress on the rails restrict the application of this technique. In the meantime, the high local current density may lead to local hot points and melt the armature. A uniform current distribution is required to prevent this damage on the armature [2].

This paper aims to propose an assembly of conductors to form a graded laminated armature and rail to obtain the maximum inductance gradient and at the same time a uniform current density in the armature. The construction of the proposed railgun is shown in Figure 1(a) and 1(b) in which Figure 1(a) shows the distribution of the current density in the ordinary railgun and Figure 1(b) gives that in a suitable assembled rail and armature with graded laminations. This is achieved by selecting different electrical conductivities for individual laminations in both rails and armature parts.

II. FINITE-ELEMENT MODEL

The finite-element method is used to calculate the inductance gradient of railgun and distribution of the current density in the armature and the rails.



(a) (b)

Figure 1. Current distribution in the right-half model of a railgun; (a) In the ordinary armature, (b) In the beveled rail and laminated armature and rail

The magnetic vector potential *A* and electric potential *V* are employed in the conduction area and only *A* in the non-conduction area. The velocity effect is neglected in the modeling. The current density distribution can found using steady-state solutions of the Maxwell equations. The electrical contact resistances between the armature and rails are assumed to be negligible during acceleration.

Furthermore, bias currents are ignored, and the magnetic permeability of the medium is set equal to the magnetic permeability of vacuum (μ_0). Using these assumptions from Maxwell equations, a system of equations for the vector and scalar potentials (A, φ) is obtained, which, for the region of conductors (armature and rails), can be written as follows:

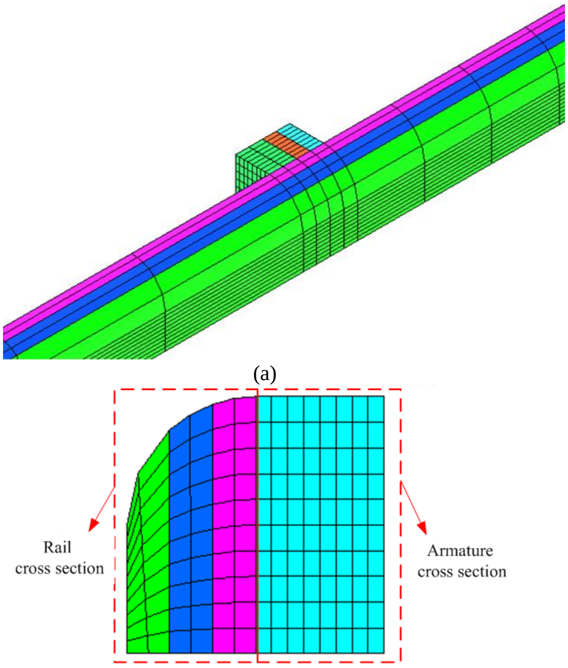
$$\vec{j} = -\frac{1}{\mu_0}\nabla^2\vec{A} = -\sigma\left(\nabla_\varphi - \vec{v}\times\nabla\times\vec{A}\right) \qquad (2)$$

$$\nabla\bullet\vec{j} = \nabla\bullet\left(\sigma\left(\nabla_\varphi - \vec{v}\times\nabla\vec{A}\right)\right) = 0 \qquad (3)$$

In the surrounding non-conducting space, where the current density $\vec{j} = 0$, Equation (2) can be expressed as

$$\nabla^2\vec{A} = 0 \qquad (4)$$

The electromagnetic part of the problem, in fact, contains one boundary condition, which requires that the components of the vector potential vanish at an infinite boundary. At all inner boundaries between the conductors and the surrounding non-conducting space, the continuity conditions for the vector-potential components and their derivatives are satisfied. As the model is symmetrical, only a quarter of it needs to be analyzed. A three-layer rail and armature model is adopted in the model. The finite-element meshes of the graded laminated armature and beveled and laminated rail with a quarter of the practical model are given in Figure 2.



(a)

(b)

Figure 2. (a) Meshes of laminated armature with beveled and laminated rail, (b) front view of railgun

III. SIMULATION AND RESULTS

In order to compare the inductance gradient and distribution of the current density in the reference railgun and proposed railgun, the reference railgun is simulated first. In this study, the reference is assumed as a simple railgun. The rails are 5×20 mm with a caliber of 10×20 mm. The rails are made of copper and the projectile is made of aluminum.

At a constant current of 80 kA, the inductance gradient and maximum current density of rails and armature are calculated using commercial software. The distribution of the current density on the rail and armature is shown in Figure 3. The calculated values for the inductance gradient and the maximum current density of armature are 0.516 μH and 3.75×10^9 A/m^2, respectively.

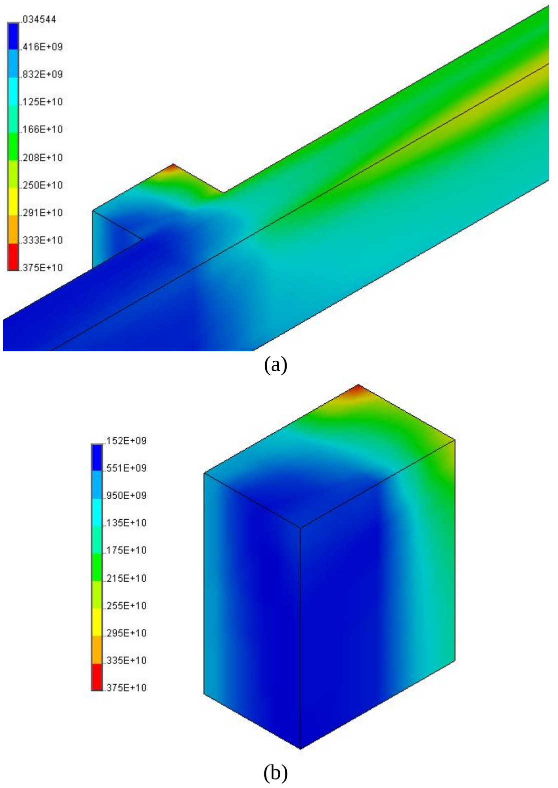
At the next step, the rails are beveled and laminated aiming to improve the inductance gradient. The resistivity combination of the constructing materials of the three-layer graded laminated rails and their widths are presented in Table 1.

The calculated results show the increase on both the inductance gradient and the maximum current density to 0.572 μH and 3.81×10^9 A/m^2, respectively. This means beveling and laminating of the rails introduces a notable increase on the inductance gradient but it deteriorates the distribution of the current density in the armature. This problem is also solved by using laminated armature. Using a three-layer graded laminated armature, the maximum current density in the armature drops to 1.98×10^9 A/m^2, showing a significant reduction of almost 50%. This also introduces a better distribution of the current density in the armature. The resistivity combination of the constructing materials of the three-layer graded laminated armature and their lengths are presented in Table 2.

The corresponding calculation results of the current density distribution on the rail and armature are shown in Figurer 4. The distribution of current density vs. distance along the movement on the armature for two aforementioned models is also shown in Figure 5.

IV. CONCLUSIONS

Inductance gradient and distribution of the current density in a railgun with beveled and laminated rails and laminated armature are calculated. It is shown that a good improvement in the inductance gradient can be obtained in case of the beveled and laminated rails. However, it deteriorates the current distribution in the armature. This problem is solved by using a graded laminated armature, where a uniform current density distribution can be achieved. In this case, the materials of the armature and the rail layers are so selected that the inner layer of the rails and at the same time the front layer of the armature have the largest conductivity. The conductivities of following layers, both in the rails and the armature are reduced from one layer to the other in predetermined step sizes as demonstrated in the paper. Validity of the proposed method is verified by using finite element method.



(a)

(b)

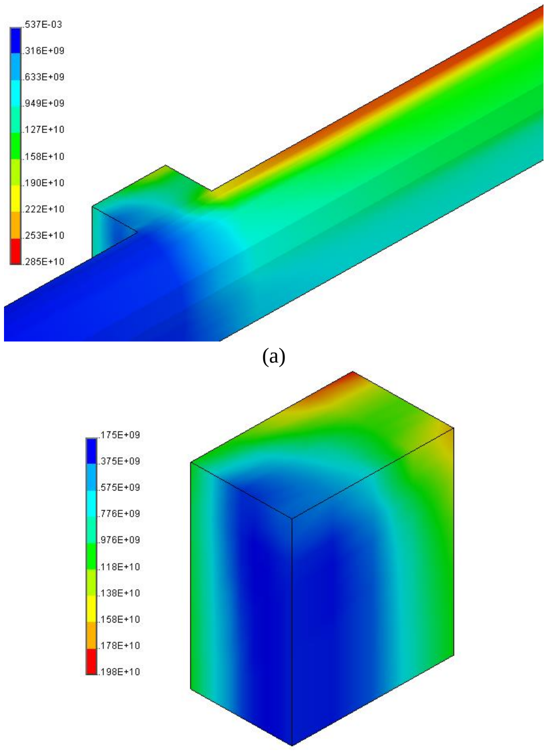
Figure 3. (a) Distribution of the current density on the reference Railgun and (b) Alone armature

Table 1. Resistivity and width of each layer for three-layer beveled rail

Rail layers	Inside layer	Middle layer	Outside layer
Resistivity (Ω.m)	2.6×10^{-8}	4.6×10^{-8}	5.6×10^{-8}
Width (mm)	1.7	1.7	1.6

Table 2. Resistivity and length of each layer for three-layer armatures

Armature layers in move direction	Rear layer	Middle layer	Front layer
Resistivity (Ω.m)	5.6×10^{-8}	2.6×10^{-8}	1.6×10^{-8}
Length (mm)	2	2	4



(a)

(b)

Figure 4. (a) Distribution of the current density on the laminated and beveled railgun and (b) Alone armature

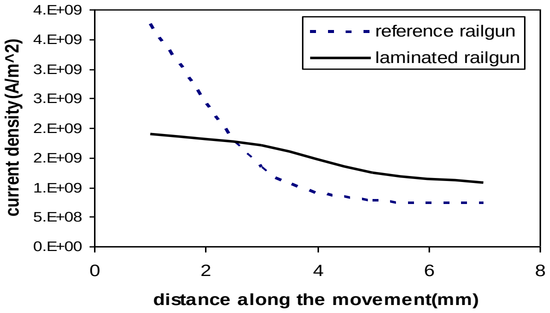


Figure 5. The distribution of current density vs. distance along the movement on the armature

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BIOGRAPHIES

Hojat Hatami was born in Urmia, Iran, in 1981. He received his B.Sc., M.Sc. and Ph.D. degrees in Electrical power Engineering from University of Tabriz, Tabriz, Iran in 2005, 2008 and 2014, respectively. In 2010, he joined the Department of Electrical Engineering at Seraj Higher Educational Institute, Tabriz, Iran. He is currently an Assistant Professor with the same institute, and now he is Head of Power Engineering Department. His employment experience included five years of cooperation with Engineering Studies Department of Mona Consultants Company, Tabriz, Iran in some regional projects of eastern Azarbaijan state in Iran. He has published several technical papers in the national and international journals and conferences. His special fields of interest included electric machines and drives, electric and hybrid vehicles, power electronics and power quality and nowadays he is working on electric machines branch.

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