Effect of Rail Tapering on the Inductance Gradient Versus Armature Position by 3D-FEM

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***Abstract*—The increasing of projectile final velocity and the uniformity of current density in the special regions of the armature and rail such as the root of the armature which is in melting are some of the purposes of the railgun design. In railgun, the applied force to run an armature is resulted from the interaction of the current passing from the armature with the magnetic field in that place. Therefore, to increase the running force and gain bigger projectile velocities, we have to increase the input current or the magnetic field between two rails per a constant current. The increasing of input current can cause more heat losses in the structure of the railgun and may cause failing of the projectile procedure because of the melting of some points of the armature or rail. High magnetic fields between rails without input stimulation increasing are possible with the application of the geometrical and structural variations in rails. The current paths in rails will be closer to each other (increasing the amount of magnetic fields between them), and so, narrowing the rail using a constant current, the current density will be bigger in the cross section of the rail. We will evaluate the effect of rail narrowing in the projectile path length with consideration of a rail length of 1 m. The narrowing procedure of the rail is defined as decreasing its cross section in the projectile path length until, in the output gate, its amount reaches zero (the height of the rail is constant). The result of simulation shows that the gradient inductance will be increased with the narrowing of the cross section of the rail in the projectile path length, and this will increase the amount of the final projectile velocity.**

***Index Terms*—Gradient inductance, narrowed rail, railgun, 3D-PEN.**

I. Introduction

An ELECTROMAGNETIC projectile structure is defined as a structure that, applying current to the rail, the armature between two rails will be accelerated and projected with a very high velocity. Gradient inductance is one of the important parameters in railgun performance design and evaluation. The rail size, shape, and material can affect the gradient inductance. The effect of rail sizes (its cross section) on the current distribution and gradient inductance was considered in [1].

The applied running force on the armature, which arises from the interaction of the armature's passing current with the existing magnetic field, is proportional to the power of two of the input current and the gradient inductance. Therefore, we can increase the input current to increase the final velocity of projectile [2], [3]. Increasing the input current in the railgun structure, acute thermal condition is produced [4], [5]. In addition, using extra rail can cause an increase in gradient inductance [6]. However, increasing the mechanical stress applied to rails can be a limited function [7].

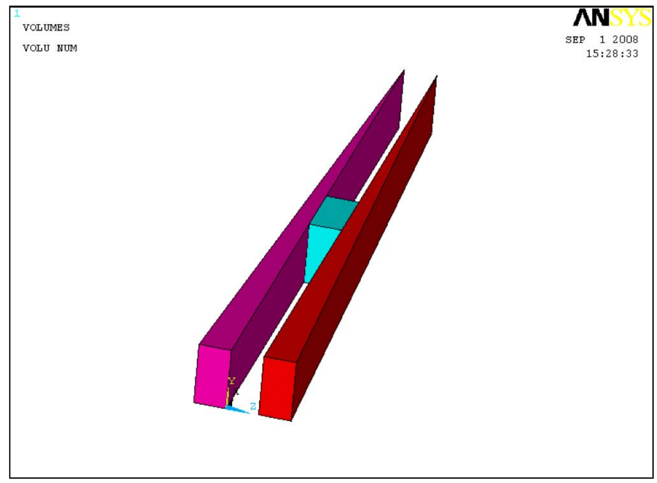

Fig. 1. Railgun with tapering rails.

The current paths in rails will be closer to each other when decreasing the amount of rail cross sections; thus, the magnetic field between them will be bigger. Moreover, the current density at the rail cross section will be bigger (for a constant current) when narrowing the rail. Because current stimulation in railgun examinations is usually produced from the discharge of capacitance between two sides of rails, this guides us to the idea that, in the projectile length path, proportional to the reduction in input current amplitude, the rail cross section will be decreased as in Fig. 1. The cross section of the rails is being tapered, and not the bore.

At the time that the current amplitude is decreased, the rail cross section is also decreased. Therefore, thermal losses in rails are not big. In addition, the rail cross section is decreased, and then, the magnetic field between two rails will be increased. Therefore, it is expected that the gradient inductance of the structure will be increased, and so, there is no current increase.

A. Governing Equations

The analysis of railgun electromagnetic is complex, and its simulation needs time transient analysis. The differential

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equation for magnetic vector potential $\vec{A}$ in the transient state is

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \vec{A}\right) + \sigma\frac{\partial \vec{A}}{\partial t} = \vec{J} \tag{1}$$

$$\nabla \times \vec{A} = \overline{B} \tag{2}$$

where $\vec{B}$ is the magnetic flux density, μ is the permeability, σ is the electrical conductivity, and $\vec{J}$ is the applied current density. The interaction between the magnetic field density produced by the rail current in the armature place and the passing current from the armature causes its acceleration in the rail length, and this force is produced from the Lorentz law

$$\vec{F} = \vec{j} \times \vec{B}\ . \tag{3}$$

By knowing the applied force on the armature in projectile direction, the gradient inductance of the structure is determined from the following equation:

$$L' = 2(F/I^2) \tag{4}$$

where F is the applied force on the armature in moving direction and I is the input current.

B. Railgun Structure and Input Current

To evaluate the effect of narrowing the rail cross section on the gradient inductance and railgun function, choosing the armature in the form of a rectangular cube with 1-cm width and the height of the rail with 8-mm length (from aluminum), first of all, we consider a railgun with a simple rail (from copper) with a length of 1 m, height of 2 cm, and width of 0.5 cm. Furthermore, in this study, the effect of rail narrowing on the projectile length path is considered. This causes its cross section in the length path of projectile to reduce until it will be zero where the rail height is constant. According to the symmetrical procedure, only one quarter of the structure is modeled. The narrowed rail of the railgun structure is shown in Fig. 1.

The current stimulation in electromagnetic projectiles is very big, and this can be done usually with capacitance discharging in two sides of rails, and its shape will be such as a pulse. Thus, the current stimulation used in simulation is shown in Fig. 2, in which, at 0.3 ms, it will increase from zero to a maximum amount of 8 kA and stay at 0.2 ms in this maximum and then decrease exponentially to zero until $t = 2$ ms.

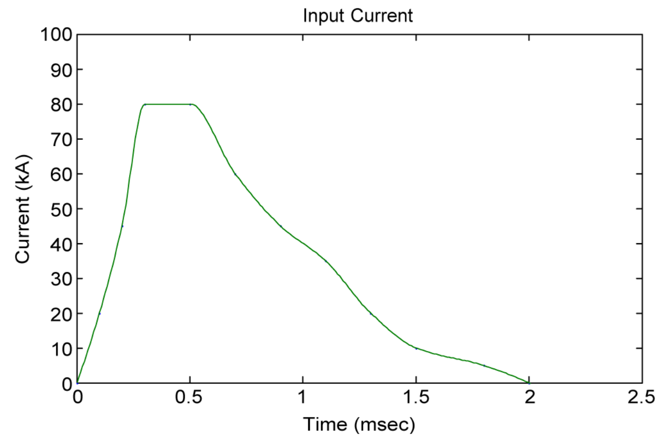

Fig. 2. Input current pulse.

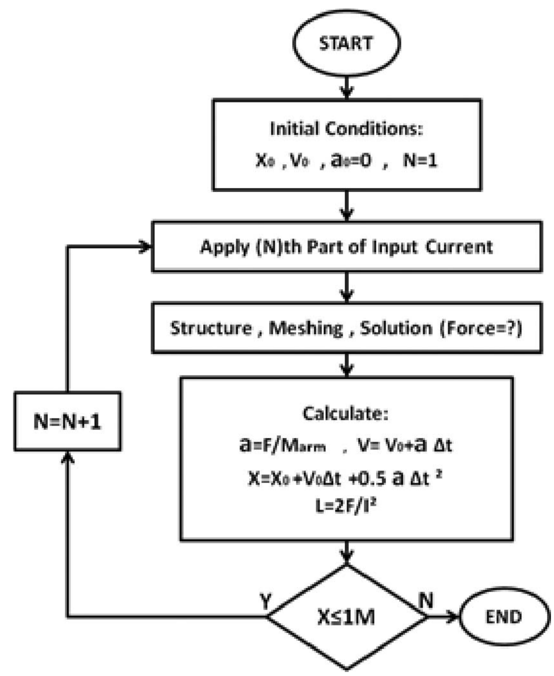

Fig. 3. Method flowchart.

II. Materials and Methods

In a simple railgun, first of all, the armature is placed 6 cm from the input, and we assume that it is in rest. The input current is divided into different elements to calculate the gradient inductance of the structure. Then, by applying every part of the input current, the applied force on the armature in moving direction will be calculated. Therefore, the gradient inductance is obtained from (4). The acceleration, velocity, and displacement of the armature are obtained by knowing the applied force on the armature. For applying the next current stimulation, we place the armature in the new position, and the method flowchart is shown in Fig. 3. It is shown in the figure that, for applying every part of the input current, we have to solve the problem. We repeat the same steps in the railgun with narrowed rails using ANSYS Software.

III. Result of Simulation

By comparing the current density distribution and force distribution in the simple railgun and the railgun with narrowed rails, it is clear that there is a little difference in the first rail, and it is in the first half of the projectile. This is completely natural because the rail width is not more reduced. In the second half of the projectile and with more reduction in rail width, it is shown that the applied force on the armature will be bigger, and it is in this time that the input current amplitude is decreasing. Thus, further cross-sectional reduction cannot cause a heat problem. The current distribution of the armature at $t = 0.7$ ms for

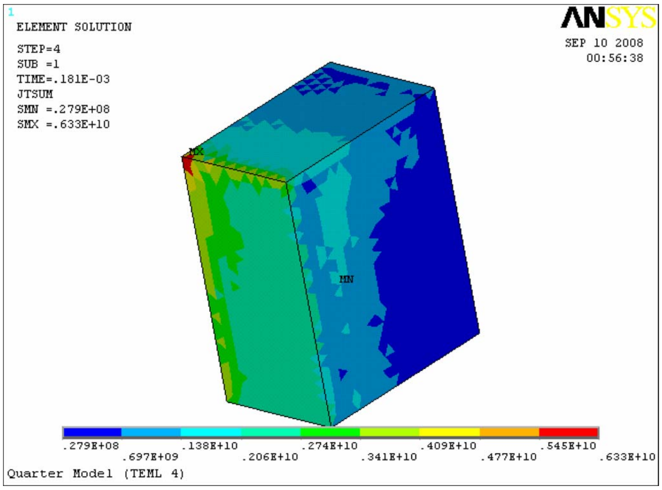

Fig. 4. Current density distribution of railgun at $t = 0.7$ ms (narrowed rail).

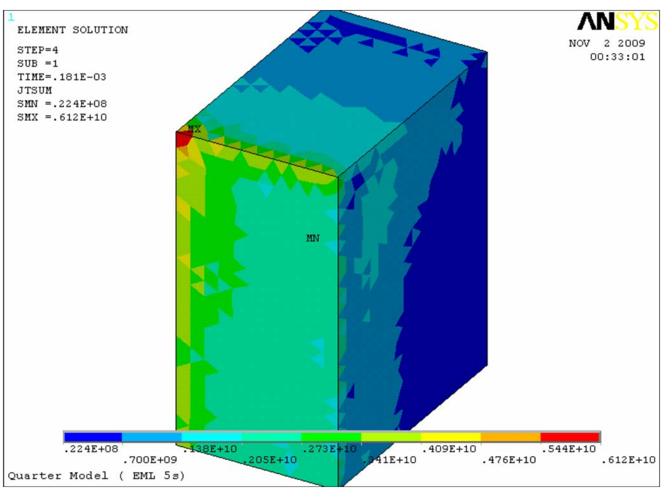

Fig. 5. Current density distribution of railgun at $t = 0.7$ ms (simple rail).

narrowed railgun is shown in Fig. 4 and, for simple railgun, is shown in Fig. 5. There is no significant difference between them unless the current density in the narrowed rail is a little more. However, it is expected that more current density is focused on the rail edges and armature. In addition, in the armature, the current density at root region is high, but most current density is at the end edge in contact of the rail.

The applied force distribution on the railgun is not more significant unless it is at the second half of projection in which the applied force on rails at Y- and Z-axes has a little increase. The force distribution in the Y-axis direction is the same as when the rail is under pressure from up and down. The applied force on rails in the Z-axis direction is as expected that it wants to separate the rails from each other. The gradient inductance in the armature place is shown in Fig 6. Gradient inductance with time transient and in rail length is increased, until $t = 1.5$ ms, to $L' = 0.574$ μH for simple rail and to $L' = 0.619$ μH for narrowed rail. In total, for far points from the edge, it is shown that the gradient inductance in rail length is increased, and in the second half of rail, the gradient inductance of the narrowed rail is bigger than that of the simple rail.

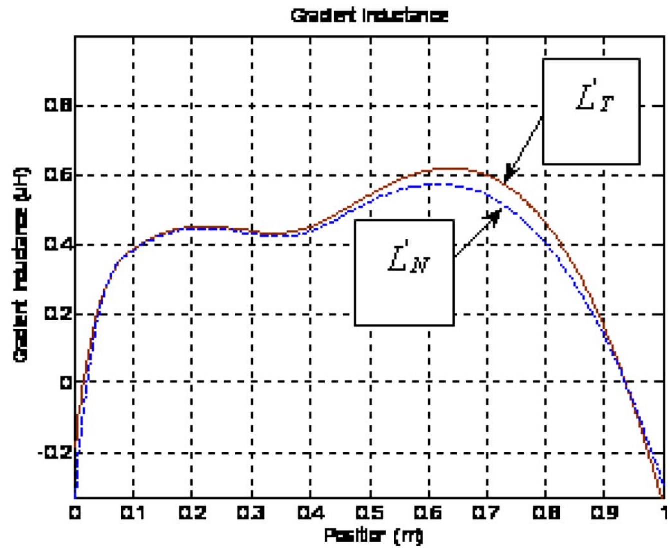

Fig. 6. Variation of gradient inductance at rail length for railgun with narrowed rail (red) and for simple railgun (blue).

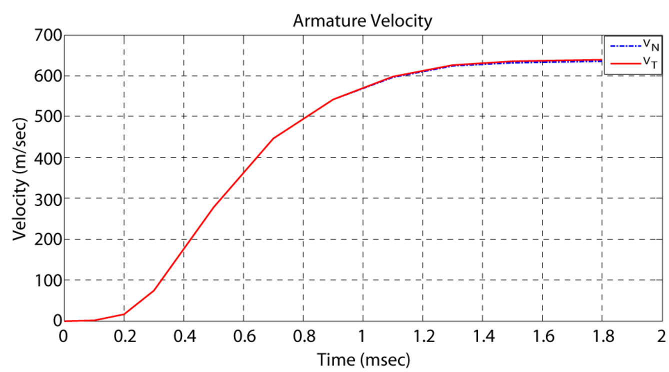

Fig. 7. Armature velocity in time.

The armature velocity in time is shown in Fig. 7. It is 650 m/s near the output which is 10 m/s more than the simple rail. There is more difference between velocities for longer rails.

IV. Conclusion

We are interested in achieving higher projectile velocities and improving the current density distribution in the structure by using finite-element codes to design and evaluate electromagnetic projectiles. Narrowing of rail cross section at the path length of projectile causes the increase in gradient inductance, in which the increase in current density distribution in the rail cross section has no bad heat effect. In these simulations, increasing the projectile velocity to 10 m/s for functional railguns with longer rails and bigger stimulation current, the difference of the output armature velocity for simple rail and narrowed rail is bigger. The evaluation of railgun when the armature is moved in rail length causes a possible study of the effect of length variations on the structure of gradient inductance, output velocity, and current distribution. There are studies which can be done in the future such as the evaluation of the effect of reduction of rail height toward the output gate and the variation of rail conduction in the projectile path length which can cause a good effect on the railgun function.

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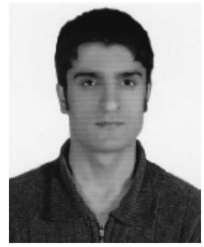

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