Transition Study of Current Distribution and Maximum Current Density in Railgun by 3-D FEM–IEM

M. Sajjad Bayati, Asghar Keshtkar, and Ahmad Keshtkar

***Abstract*—The intelligent estimation method (IEM) is based on approximations which can be described by the configuration and behavioral characteristic of the problem. This paper used the IEM in time domain (IEM-TD) which can be utilized to predict the current distribution and maximum current density. A detailed IEM technique to compute the current distribution over the surface of a rail, current profile around the rail, and maximum current density ($J_{\max}$) formula will be presented in this paper. The current distribution is computed for rectangular and circular rails that are shown in color figures. Finally, this paper considers the effect of the rail dimensions and material on these parameters that are shown in several figures. The results of this paper are compared to other published studies and FEM simulation.**

***Index Terms*—Circular, current density, IEM-TD, maximum, railgun, rectangular.**

I. Introduction

The CURRENT density distribution and maximum values in high-power systems are important factors in designing a railgun. The geometry, dimensions, and material of the railgun can change the value and profile of the current density in the rail and armature. For the past several years, many papers have focused on computing the current distribution by using numerical methods. In these research studies, they computed the effect of rail dimensions [1], geometry of the armature [2], [3], rail material [4], and graded laminated armature [5] on the current distribution. The intelligent estimation method (IEM) that can be utilized to compute the current density distribution and maximum current density was presented by Keshtkar *et al.* [6] to solve the nonlinear problem in electromagnetic domains. This technique is based on approximations which can be described by the configuration and behavioral characteristic of the problem.

This paper used the IEM to derive the current distribution over the rail cross section and the current profile around the rail in rectangular and circular railguns. The closed formula of the maximum current density can be described by a function of the railgun dimensions, material, and time variation which is obtained by using the IEM.

In the next section, this paper considers the effect of the rail dimensions and materials on the maximum current density. Finally, the results of this paper are shown in several figures which are compared to the results of other published papers and FEM simulation.

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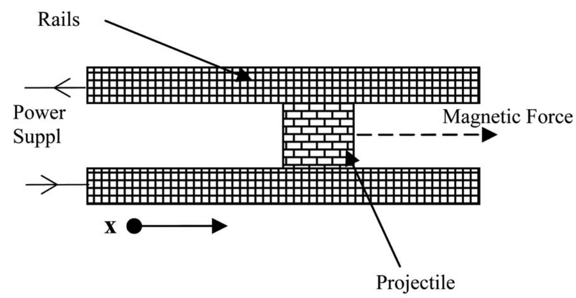
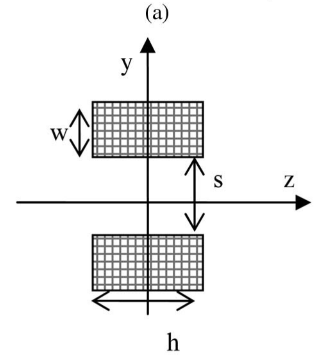


(a)



(b)

Fig. 1. Simple railgun. (a) Structure of railgun in 3-D case. (b) Cross section of railgun.

II. Problem Statement

A simple structure of a railgun with a moving armature in the x-direction consists of two parallel rails, an armature, and a power supply, as shown in Fig. 1, [6].

The IEM technique can be utilized to calculate the current distribution. The complete report and the various iterations of the IEM-TD implementation are expressed in [7]. To summarize, the structure of the case study needs to get recognized correctly. This involves the consideration of all influential parameters such as physical dimensions, material, time-variation characteristics, thermal effect, and any other environmental conditions.

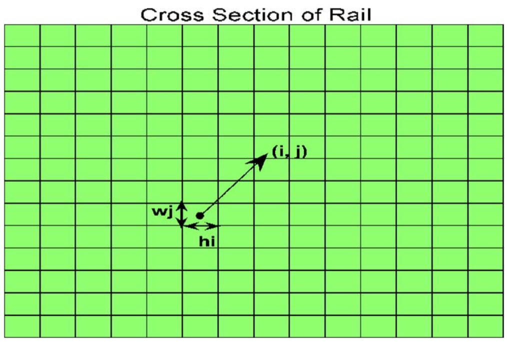


Fig. 2. Grid of rail cross section.

Although some essential knowledge about the geometry and physics of the problem is needed in this method, the simplicity and the less time-consuming characteristic are the main advantages of the IEM in time domain, which let us derive a formula for any given structure with a moving armature.

A. Current Density Distribution

According to (1), the inductance gradient of a railgun which was obtained in [6] depended upon the width, thickness, and separation.

$$L' = \frac{10^{-6}}{\frac{0.5986h}{s} + \frac{0.9683h}{s+2w} + \frac{4.3157}{\ln\left(\frac{4(s+w)}{w}\right)} - 0.7831} \tag{1}$$

where w, s, and h are the thickness, separation, and width of the rail, respectively.

The driving force acting on the projectile is given by the following equation [8]:

$$F = \frac{1}{2} L' I^2 \tag{2}$$

where L', I, and F are the inductance gradient, driving current in the armature, and projectile force, respectively.

The total current flow through the rail is given by

$$I = \sqrt{2F_c/L'} \tag{3}$$

where F_c and L' are the constant force and inductance gradient, respectively.

A meshing model of the cross section of the rail is shown in Fig. 2 which is divided by an $m \times n$ element wherein the size of each element can be computed by

$$h_i = \frac{h}{m}, \qquad w_j = \frac{w}{n} \tag{4}$$

where h_i and w_j are the size of the grid.

$$I_{(i,j)} = \sqrt{2F_c/L'(h_i, w_j)}$$
$$J_{s(i,j)} = \frac{I_{(i,j)}}{(h_i \times w_j)} \tag{5}$$

where $L'(h_i, w_j)$, $I_{(i,j)}$, and $J_{s(i,j)}$ are the inductance gradient, current, and current density over the surface for element (i, j), respectively. The total current density over the cross section of the rail is

$$J_s = \sum_{i=1}^{m} \sum_{j=1}^{n} J_{s(i,j)}. \tag{6}$$

The profile of the current density around the rail cross section can be computed by

$$J_{h1} = \sum_{i=1}^{m} \left(J_{s(i,1)} - J_{s(i,2)}\right) w_j$$
$$J_{hn} = \sum_{i=1}^{m} \left(J_{s(i,n-1)} - J_{s(i,n)}\right) w_j$$
$$J_{w1} = \sum_{i=1}^{n} \left(J_{s(1,j)} - J_{s(2,j)}\right) h_i$$
$$J_{wm} = \sum_{j=1}^{n} \left(J_{s(m-1,j)} - J_{s(m,j)}\right) h_i \tag{7}$$

where J_{h1}, J_{hn}, J_{w1}, and J_{wm} are the current densities around of the rail cross section.

B. Maximum Current Density

The maximum current density has been produced at the rail inner edges so that it can produce a hot point which fuses the rail edges and should be considered in railgun designing. The aforementioned phenomenon occurs when separation (s) is also decreased. The size of the rail cross section and the angle of the rail corner at the inner edge are decreasing which could be caused to increase the $J_{\max}$.

This paper suggested an initial formula to show the effect of separation (s), width (h), and thickness (w) on $J_{\max}$ which is achieved by structure geometry which is shown in the following:

$$J_{\max} \propto \left(\frac{C_1}{\sqrt{h'^2 + w^2}} + \frac{C_2}{\sqrt{s'^2 + w^2}} + C_3\right). \tag{8}$$

In addition, the basic behavior of current and electromagnetic fields in such good conductors will be decreased by increasing the length of the rail. It is evident that the magnitudes of the fields and current decrease exponentially. It can change the $J_{\max}$ values. Thus, $J_{\max}$ is defined by

$$J_{\max} \propto e^{-\alpha x} \tag{9}$$

where α and x are the attenuation constant and the location of the armature along the rail, respectively.

The attenuation constant can be computed by

$$\alpha_i = \ln\left(\frac{Magnetic\ Energy}{Source\ Energy}\right) \Big/ 2x_i. \tag{10}$$

By combining (8) and (9), an initial formula can be defined as

$$J_{\max} = \left(\sum_{i=1}^{5} A_i e^{-\alpha_i x}\right) \times \left(\frac{C_1}{\sqrt{h'^2 + w^2}} + \frac{C_2}{\sqrt{s'^2 + w^2}} + C_3\right)$$
$$h' = k_{\rm h} h, \quad s' = k_{\rm s} s \tag{11}$$

where α_i, k_h, and k_s are the attenuation constant and the efficiency factor to thickness and separation, respectively. A_i and C_i are the weighting coefficients.

By using (10), the values of the attenuation constant are computed.

$$\alpha_1 = 10.1829 \quad \alpha_2 = 9.2415 \quad \alpha_3 = 7.9872$$
$$\alpha_4 = 4.7032 \quad \alpha_5 = 2.8128 \tag{12}$$

The weighting coefficients in (11) can be calculated by using some numerical results. The values of these coefficients are as follows:

$$A_1 = 3.6743 \quad A_2 = -6.8560 \quad A_3 = 3.5752$$
$$A_4 = -0.4808 \quad A_5 = 0.1307$$
$$C_1 = 0.2997 \quad C_2 = 0.1349 \quad C_3 = -2.6639$$
$$k_h = 2.250 \quad k_s = 1.75. \tag{13}$$

The obtained formula could be used to calculate the maximum current density in a railgun without simulation or testing.

The rail and armature conductivity can changed the value of the maximum current density. This paper presented a conductivity factor (k_c) to model the effect of conductivity on $J_{\max}$, which is computed by using the boundary condition between the rail and armature

$$k_c = (\rho_{1r} + \rho_{1a})/(\rho_{2r} + \rho_{2a})$$
$$\frac{J^2_{\max}}{J^1_{\max}} = (\rho_{1r} + \rho_{1a})/(\rho_{2r} + \rho_{2a}) \tag{14}$$

where k_c, ρ_r, and ρ_a are the conductivity factor, rail resistivity, and armature resistivity, respectively.

III. Results and Comparison

Different values for thickness, width, and separation are used in this paper to consider the effect of the rail size on the current distribution and $J_{\max}$ which is shown in several figures. The comparison of the current distribution results and the values of $J_{\max}$ were determined by other reported research studies and FEM simulation; in this paper, the results are shown in several figures that show a good agreement between these results.

A. Current Distribution

For $h = s = 20$ mm and $w = 10$ mm, the current density over the cross section of the rectangular rail can be given by (6), which is shown in Fig. 3.

Fig. 4 shows the current distribution over the cross section of the circular rail. Fig. 5 shows the current density around the surface of the 4 mm × 2 mm rail, which is compared with the results in [9]. Figs. 6 and 7 show the current density over the rail cross section as a function of the rail width, which is compared with that in [8].

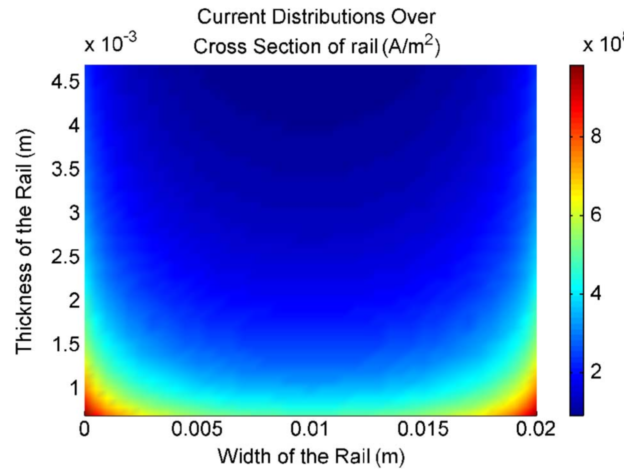


Fig. 3. Current distribution over the cross section of rectangular rail.

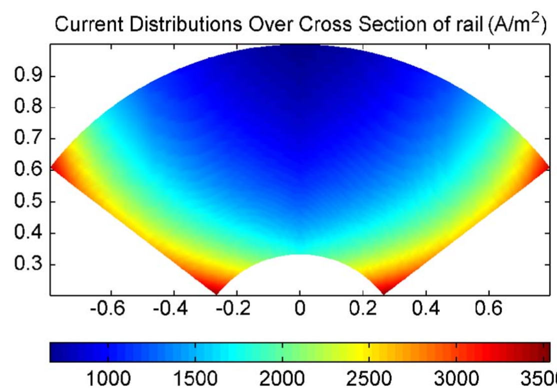


Fig. 4. Current distribution on the cross section of circular rail.

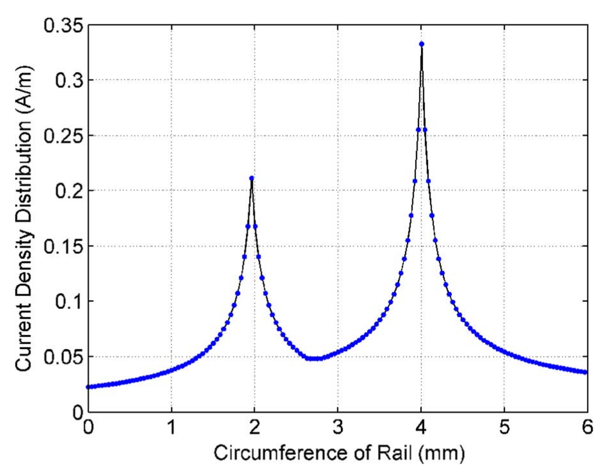


Fig. 5. Current distribution as a function of the rail circumference. (— • —) Results of this paper. (— • —) Results of [9].

B. Maximum Current Density

Figs. 8 and 9 illustrated the negligible difference between the $J_{\max}$ computed using the formula in this paper and the $J_{\max}$ obtained using FEM simulation. To illustrate the effect of the different values of w, s, and h on $J_{\max}$, the $J_{\max}$ formula is used to compute that are shown in Figs. 10 and 11. Fig. 12 shows the $h \times w = 4$ cm^2 as function of the s. The maximum current density is reduced if the w is reduced and the h and

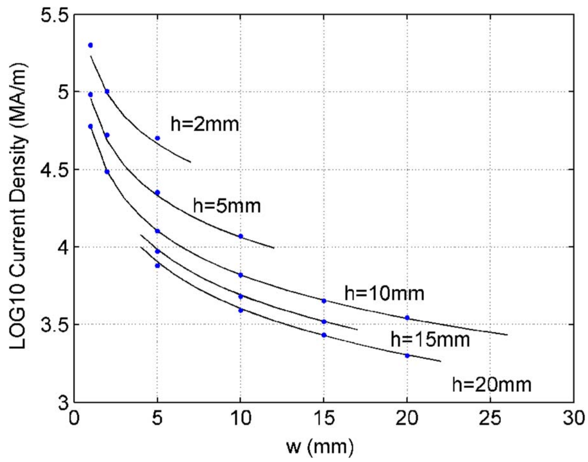


Fig. 6. Current density over the cross section of the rail as a function of the rail width. (—) Results of this paper. (— · —) Results of [8].

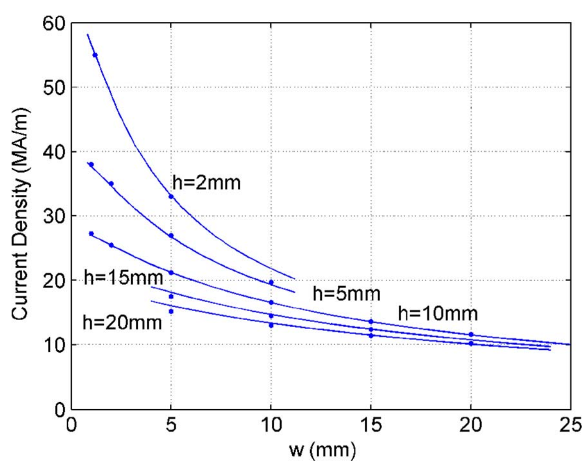


Fig. 7. Current density circumference of the rail as a function of the rail width. (—) Results of this paper. (— · —) Results of [8].

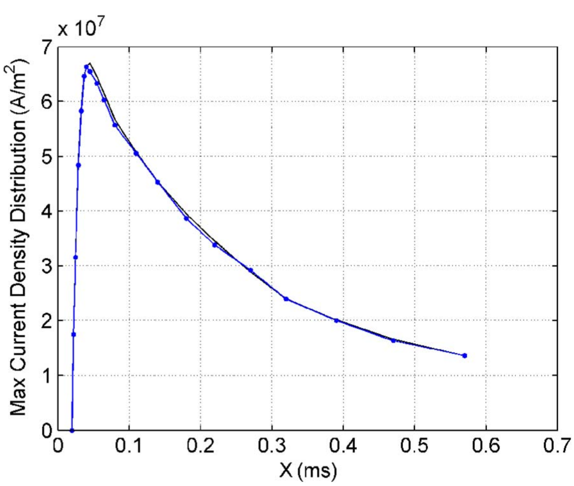


Fig. 8. Extracted $J_{\max}$ along the rail. (— · —) Results using FEM. (—) Results using the method in this paper.

s are increased. The obtained results for different armature conductivities using (14) and FEM simulation are shown in Fig. 13.

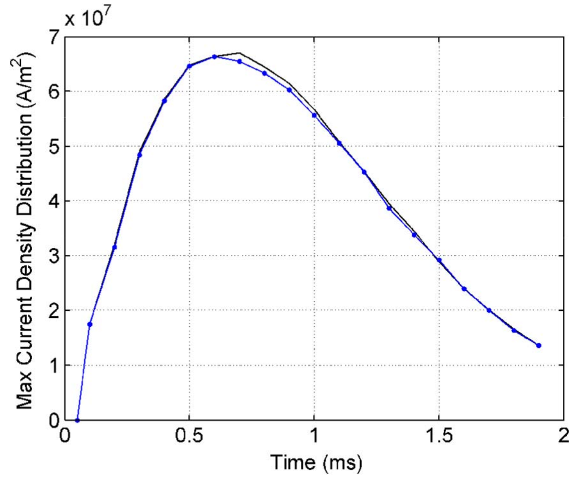


Fig. 9. Extracted $J_{\max}$. (— · —) Results using FEM. (—) Results using the method in this paper.

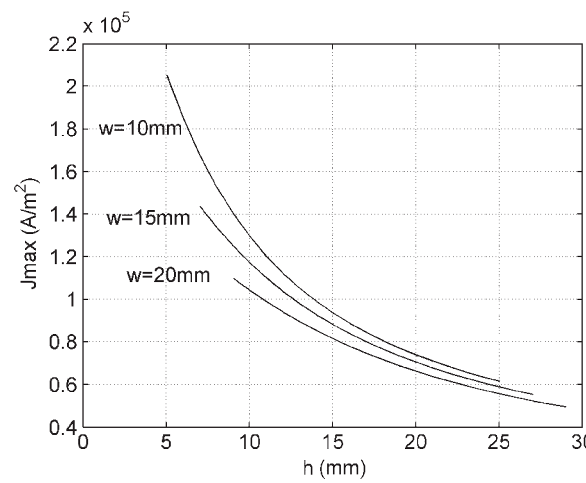


Fig. 10. Extracted $J_{\max}$ versus w as a function of the rail height (h).

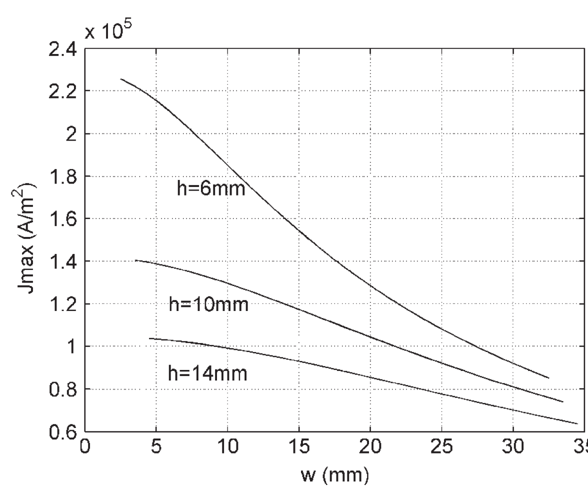


Fig. 11. Extracted $J_{\max}$ versus h as a function of the rail thickness (w).

IV. Conclusion

In this paper, a novel method has been introduced to derive the current distribution and the maximum current density by combining analytical and numerical methods under the concept

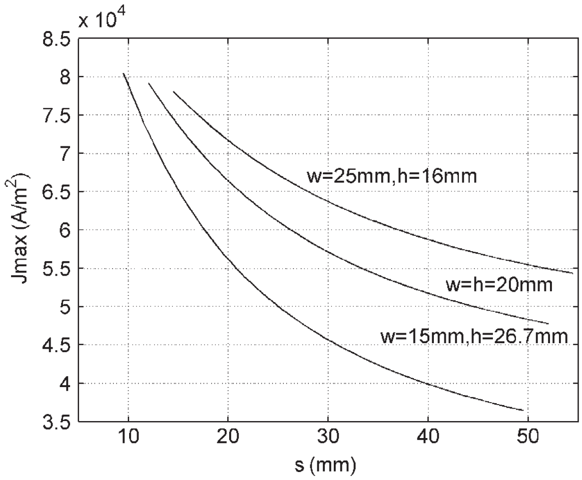


Fig. 12. Extracted $J_{\max}$ versus w and h as a function of the rail separation.

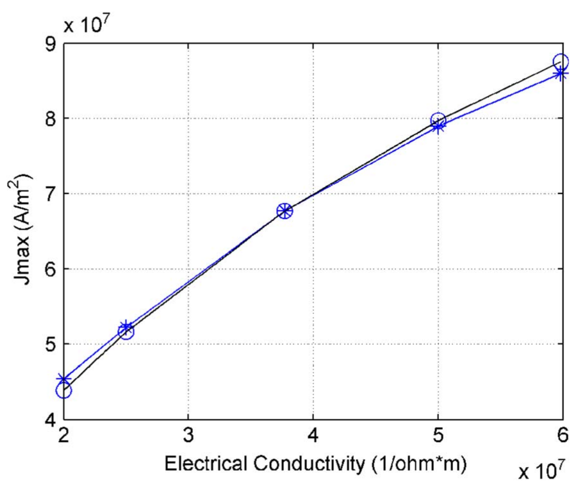


Fig. 13. Extracted $J_{\max}$ versus conductivity. (— O —) Results using FEM. (—*—) Results using the method in this paper.

of the IEM. It should be noticed that the critical advantage of utilizing the IEM is preparing an enormous ability to develop a simplified general governing formula to sufficiently describe any analytically complicated structures. Finally, the IEM is used to derive a general formula for the maximum current density in rectangular railguns. Comparing to other published papers, our formula has satisfied their numerical results with slight differences. The maximum current density formula could be applied to solve the low mean lifetime problem of the rectangular railguns.

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