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Research paper

Inductance gradient and current density distribution for T-shaped convex and concave rail cross-sections

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Abstract

Rectangular rail was the most widely used cross section shape for the rail gun electromagnetic launching (EML) system. Based on sector assimilation, the rail gun key parameter especially current density (J) and inductance gradient (L') greatly affected. J decides the efficiency of EML and L' decides the force acting on the projectile of EML. So, it is mandatory to look upon the sector assimilation of rails. In this paper T shape convex and concave shape rail cross section is proposed and rail gun key design parameters are calculated by varying its dimensions using Ansoft Maxwell 2-D eddy current solver which uses finite element analysis technique to calculate these parameters. The performance of rail gun discussed using the obtained values and it has been observed and that the compared with other considered rail geometries, the T-shaped concave model shows more impact on inductance value which causes uniform current density distribution over the rails.

Keywords: *EML; Sector Assimilation; Current Density Distribution; Inductance Gradient and Finite Element Analysis.*

1. Introduction

Railgun is a three dimensional electromagnetic launching system that works under the basic principle of Lorentz force. The performance of EM launch depends on inductance gradient (L') and Current density distribution (J). J decides the efficiency of EML and L' decides the force acting on the projectile of EML. The value of L' can be enhanced and J value minimized by concentrating on geometry of the system. The current supplied to the rails (I) and inductance gradient of the rail plays key vital role in rail gun design which directly determines the accelerating force for the projectile by the equation, [1].

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

From equation (1), it is inferred that the force which is used to accelerate the projectile is directly proportional to the L' of the rails when the current supplied to the rails keeping as constant [2]. The quantity of electrical energy which is supplied to the rails is translated in to mechanical energy depending on current density distribution over the rail and armature. As the current density (J) and L value varies by changing shape and dimensions of rail and armature [3].Since the current is provided merely in fraction of time to the rails and determining these two parameters are complicated for a specified rail system as the current density distribution is not uniform. For many years' researchers being carried out to evaluate Inductance gradient (L') and current density for rectangular rails by varying its width (W), height (H) and separation (S) between the two rails. In general, the inductance gradient can be found by analytical and numerical methods. Analytical will be suitable for solving simple problems and programming codes were used for numerical methods which is time consuming process. JianxinNie *et al*. derived an proposed analytical expression from Batteh's formulae [4]–[6] by introducing rail thickness and skin depth. Here, they considered rail and armature parameters for deriving L' which gives an accurate result [7]. To make this process simple, regression method is used to compute the value of inductance gradient. On changing the rail dimensions the calculated L' values were entered in curve fitting software that gives a best equation for computing the inductance gradient value [8], [9]. Asghar Keshtkar *et al.* [10] have investigated the effects of rail dimensions on L' and current density values for the rectangle shape rail gun and also developed a simple mathematical expression which is used to calculate inductance gradient rail under high frequency limit. The effects of rail dimensions on L' and current density (J) values for the rectangle caliber railgun and has given a extracted empirical formula which is used to calculate inductance gradient of the rail under high frequency using IEM method[11]. In fact, various techniques have been made to evaluate the inductance gradient of rails with rectangle cross section. Now a day's researchers are focusing to determine L' and current density value by changing the rail shape and its dimensions. As the time harmonic frequency increases the inductance value decreases. This is because of the skin effect. To reduce this effect, the small change in the input current has to be maintained as small as possible [12]. For the various geometries of rail cross sections like rectangular, circular, or along with concave and convex models, the L' and J values were calculated and compared with the results obtained [13]-[16]. In this paper T shape convex and concave shape rail cross section is proposed and rail gun key design parameters are calculated by varying its dimensions using Ansoft Maxwell 2-D eddy current solver which uses finite element analysis technique to calculate these parameters.

2. Simulation setup

The rail gun is a three dimensional device. But by assuming the rail gun barrel to be infinitely long enough then the electromagnetic performance of rail gun model can be investigated with the 2-D finite element model for the cross section of the barrel normal to the longitudinal direction. Ansoft Maxwell simulation software is employed with input current of 300kA with frequency of 2kHz to calculate the inductance gradient and current density of the rails. Copper material is chosen for rails with conductivity of 5.8 x 107 S/m and relative permeability of 0.999991 H/m. The geometric dimensions parameters of rectangular rail cross section (H= 40mm, W=10mm, S=30mm)[3] and T-shaped rail of different cross section[3] (H=40mm, W=10mm, S=30mm, maximal d=10mm and minimal m=2mm, radius, (r1) = 7.5mm)shown in Fig.1 considered for extending the analysis in this work.

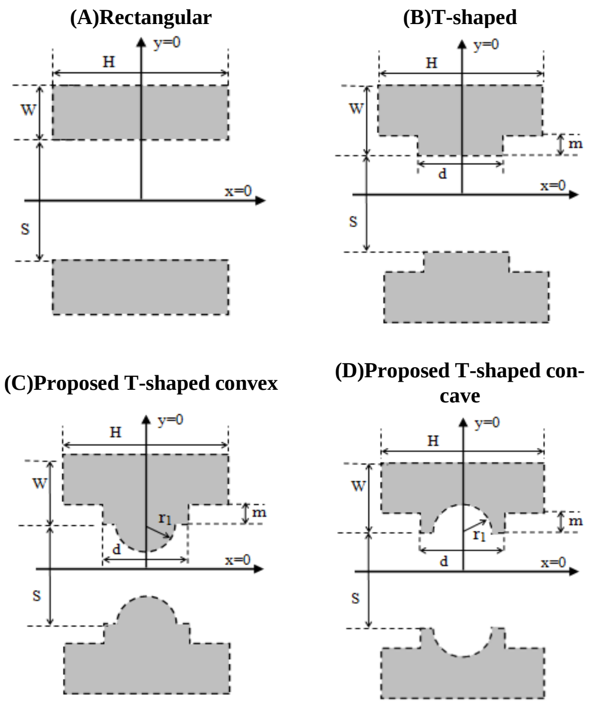


Fig.1: Rectangular and Various T-Shaped Rail Cross Sections.

3. Rectangular and t shaped rail cross-section

The dimensions of a simple typical geometry of the rectangle and T shape cross section of the rails are considered as H= 40mm, W=10mm, S=30mm and H=40mm, W=10mm, S=30mm, maximal d=10mm and minimal m=2mm [3]. The current density (J), inductance gradient (L') are calculated for the above dimensions and the obtained L' value was 0.46705 (μH/m) for 2000 Hz which is higher value compared with Zhou's [3] result 0.532 (μH/m) for 60 Hz since the inductance gradient (L') decreases as frequency increases.

4. Performance of rail gun for proposed t-shaped rail cross section

Current density distribution and Inductance gradient plays a vital role on the EM launching system. Higher the value of inductance gradient (L') results in hypervelocity of the projectile. The magnitude of force depends on the current density distribution (J) and the magnetic flux density (B) over the rails. For a short instant of time, when high frequency of supply current passed through the conducting rails it will tends to pass through the surface of the conductor by increasing the resistance gradient which results in Skin effect, which will affect the L' value and current density distribution [16]. While implementing in the actual system, this effect can be reduced by the laminating technique for the whole system, which may tends to uniform current density distribution [17]. The Proposed symmetrical cross sectional models for T-shaped rails have been simulated by FEM and L' and J values are calculated for various values of minimal (m) values and tabulated in table1 and table 2.

From the tabulations it has been observed that, the inductance gradient (L') and current density values increases on increasing minimal m and decreases on increasing maximal d for each model. It is also observed that, L' and J values for T-shaped Concave rail cross-section were higher values when compared with T-shape rail cross section and T-shaped convex rail cross-section. The Current density distribution and magnetic flux density field plots for various rails shapes of rail cross section shown in fig.2.

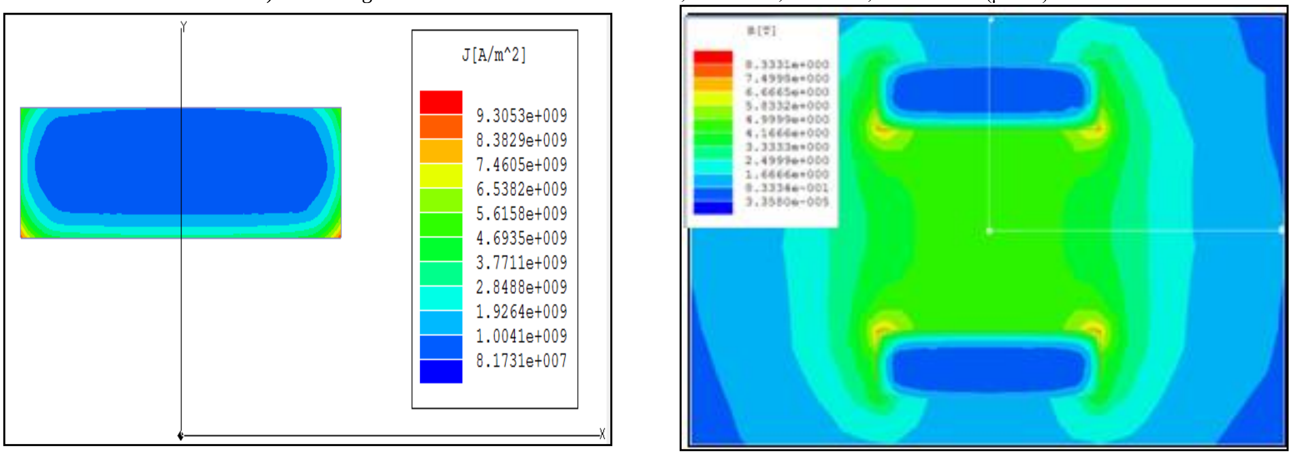
Table 1: L' (μH/m) Values for the Proposed T-Shaped Rail Cross-Sections

m (mm)	T Shaped (H=40mm, W=10mm, S=30mm,)			T shaped Convex H=40mm, (W=10mm, S=30mm,r_1=7.5mm)			T shaped Concave H=40mm, (W=10mm, S=30mm,r_1=7.5mm)		
	d=10mm	d=20mm	d=30mm	d=10mm	d=20mm	d=30mm	d=10mm	d=20mm	d=30mm
2	0.49932	0.49155	0.48256	0.47936	0.47444	0.46677	0.50605	0.49641	0.48721
4	0.52815	0.51198	0.49343	0.50352	0.49275	0.47719	0.5367	0.51726	0.49861
6	0.55222	0.52786	0.5015	0.52397	0.50756	0.48463	0.56228	0.53414	0.50703
8	0.57459	0.54267	0.50873	0.54244	0.52056	0.49127	0.58574	0.54908	0.51423

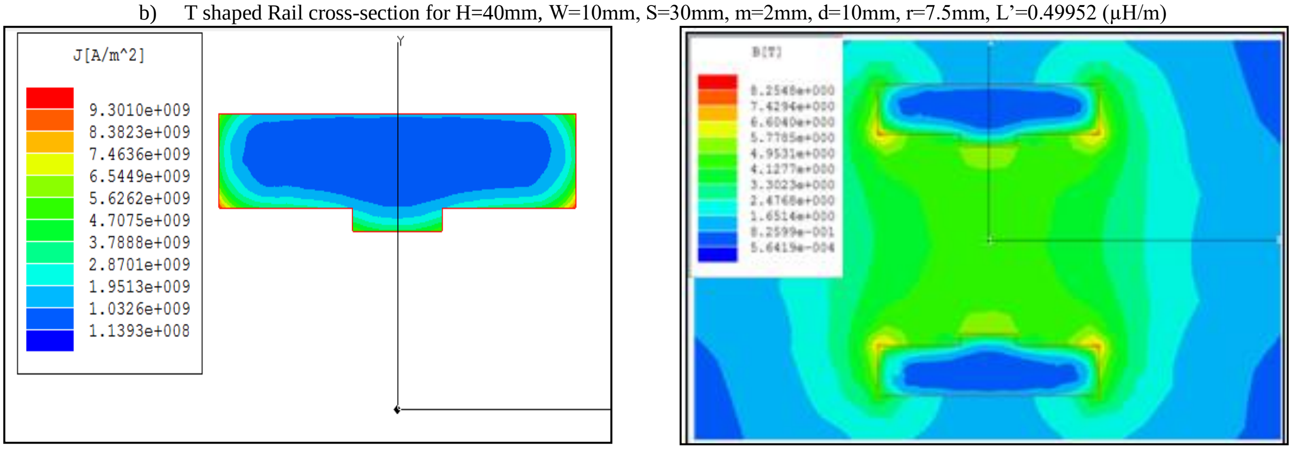
Table 2: Current Density ($J \times 10^9$) (A/m^2) Values for the Proposed T-Shaped Rail Cross-Sections

m (mm)	T Shaped (H=40mm, W=10mm, S=30mm,)			T shaped Convex H=40mm, (W=10mm, S=30mm,r_1=7.5mm)			T shaped Concave H=40mm, (W=10mm, S=30mm,r_1=7.5mm)		
	d=10mm	d=20mm	d=30mm	d=10mm	d=20mm	d=30mm	d=10mm	d=20mm	d=30mm
2	9.3010	9.2111	8.5407	8.8790	8.7405	8.3755	9.5237	9.2254	8.8009
4	9.5203	9.1765	8.0801	8.9180	8.4674	7.7101	9.7977	8.9687	8.2598
6	9.7267	8.9193	8.7592	9.0897	8.4845	8.4926	11.006	9.0005	8.9652
8	11.288	10.166	9.3311	10.522	9.7798	9.0694	12.151	10.284	9.4967

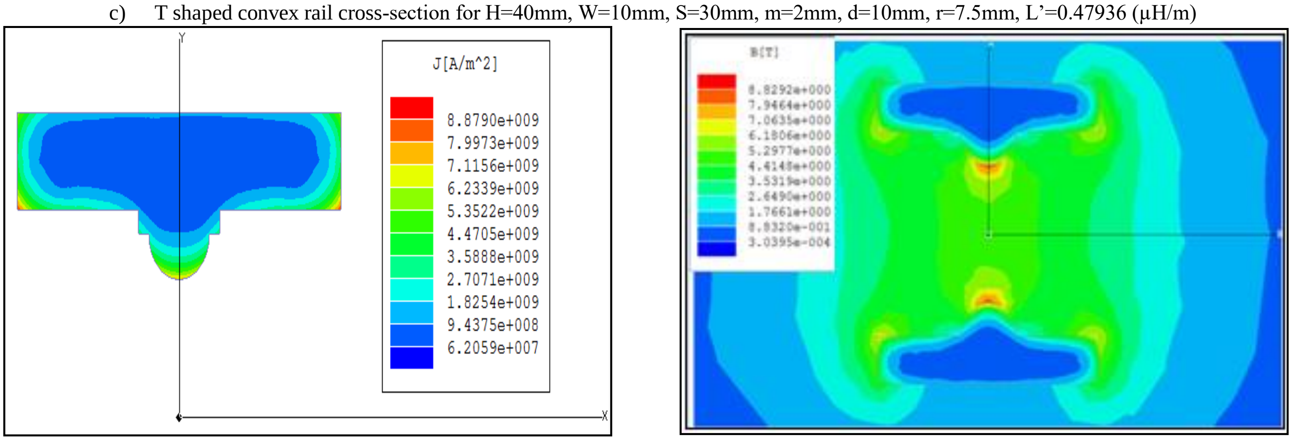
a) Rectangular Rail cross-section for H=40mm, W=10mm, S=30mm, L'=0.46705 (μH/m)



b) T shaped Rail cross-section for H=40mm, W=10mm, S=30mm, m=2mm, d=10mm, r=7.5mm, L'=0.49952 (μH/m)



c) T shaped convex rail cross-section for H=40mm, W=10mm, S=30mm, m=2mm, d=10mm, r=7.5mm, L'=0.47936 (μH/m)



d) T shaped concave Rail cross-section for H=40mm, W=10mm, S=30mm, m=2mm, d=10mm, r=7.5mm, L'=0.50605 (μH/m)

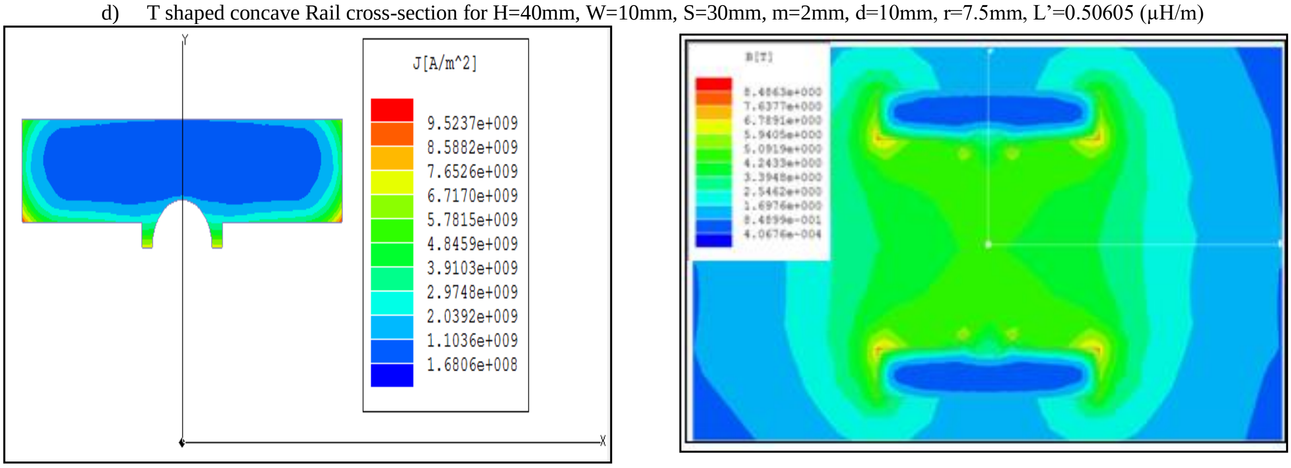


Fig. 2: Current Density Distribution and Magnetic Flux Density Field Plot for Different Rail Cross Section.

From the figures it is observed that the current and magnetic flux density of rail mainly distribute in external surface region, it is also observed that, current density in the interior wall is higher than that of exterior wall, the highest current density materialized in two inside corner points.

5. Conclusion

This paper investigates the effect of rail dimension on rail gun design parameters for the proposed rail cross section of T-shaped rail. Inductance gradient (L') and current density distribution (J) for the different T shaped rail cross-sections are calculated by varying the geometric dimensions of the rails. On this investigation it has been observed that the inductance gradient (L') and current density values increases on increasing minimal m and decreases on increasing maximal d for each model. It is also observed that L' and J values for T-shaped Concave rail cross-section were higher values when compared with T-shape rail cross section and T-shaped convex rail cross-section. Therefore, compared with other considered rail geometries, the T-shaped concave model shows more impact on inductance value (0.48721μH/m) which causes uniform current density distribution over the rails.

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