Effect of Rail Dimensions on Rail Gun Design Parameters

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***Abstract* – The purpose of modeling the rail gun is to provide a theoretical understanding of how the design parameters of rail gun such as magnetic flux density between the rails, maximum current density over the rail cross section, repulsive force acting on the rail, and inductance gradient of the rail react under different conditions like the boundary conditions and variation in dimensions. Finite element analysis technique is employed to calculate the rail gun design parameters using two-dimensional analysis. The rail gun design parameters mainly depend on rails and armature, geometry and dimensions. This paper investigates how the rail dimensions affect the rail gun design parameters using finite element technique.**

***Keywords* - Finite Element Method, Inductance gradient, Current density, Rail force, Flux density**

I INTRODUCTION

The rail gun is a device used to launch a projectile using electromagnetic energy. It uses the magnetic field generated by the rail current to accelerate the projectile between the conducting rails. The design of rail gun depends on the inductance gradient of the rail, magnetic flux density between the rail, maximum current density over a rail cross section and repulsive force acting on the rails. In a practical case very high magnitude and short duration of current pulse is applied to the rail. Since the time is short the current does not penetrate the rails or armature completely. Hence the analysis of these parameters during the firing condition is difficult. In order to gain a quantitative understanding of these parameters it is desirable to calculate these parameters well in advance. The magnetic flux density between the rail and inductance gradient of the rail plays an important role in the performance of rail gun and it determines directly the force that accelerates the projectile. The current density distribution is not uniform over the cross section of rails. In this case, the current is distributed very high near the surfaces of each conductor. This makes the electromagnetic analysis of the rail gun extremely complex. In general these values are affected by number of parameter such as velocity of the moving armature, armature geometry, rail geometry, rail dimensions and armature and rail materials [1]. Previously various mathematical model and code [2], [3] were developed to compute the rail gun design parameters. Also the researchers focused on the computation of Inductance gradient, current density distribution [4], [5], [6] and magnetic flux density [7],[8] and measurement of it. The objective of this investigation is to determine the current densitydistribution over a rail cross section, magnetic flux density between the rail, inductance gradient of the rail and repulsive force acting on the rail with respect to rails dimensions using finite element technique.

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II. THEORETICAL ANALYSIS AND GOVERNING EQUATIONS

A. Maximum Current density over rail cross sections (J_A)

There are several rail gun applications in which it is desirable to have a solid conducting armature which complete the current path between the rails. As a very high value of current and short duration pulse is applied to the rail gun, the current distribution is not uniform over the cross section. In this case, current is distributed in a very thin layer near the surface of each conductor that is called skin depth.Moreover the current density is higher at the rail inner edges. This phenomenon produces a hotspot that fuses the rail edges. In order to prevent rail gun from damage due to ohmic heating and internal forces, it is necessary to understand and model the current density distribution within the conducting medium.

B. Magnetic flux density between the rails (B)

The magnetic field between the rails plays an important role in rail gun as it produces force on the projectile. The current flows through one rail, passes through the armature, which travels perpendicular to the rails, and passes through parallel to the other rail. As a result the two rails produce the magnetic field between them. The current through the armature interacts with this field and experiences a force. The magnetic flux between the rails is summation of the field due to the rails and armature. But field contribution due to armature is negligible (9). Hence taking this account the total magnetic field between the rails is calculated only due to the rails.

C. Inductance gradient or inductance per unit length of the rails (L').

Inductance gradient of the rails plays an important role in a rail gun design, as it determines the efficiency of the rail gun

(10). Efficiency of the rail gun is defined as ratio of projectile energy to input energy. To improve the efficiency various geometry and dimensions of rails and armature are used. Acceleration force and L' could be investigated instead of efficiency. These are related by the following equation

$$F = (1/2)L'I^2 \quad (1)$$

where L' is the gradient inductance or inductance per unit length of the rails, I is the driving current and F is the force exerted on the armature.

The Inductance gradient of rail is calculated using the relation

$$L' = 2E_m/I^2 \quad (2)$$

where E_m is the energy stored in the rails is the current in the rails

D. Repulsive force acting on the rails (Fr)

In a rail gun the current flowing through one rail interact with the field produced by the current flowing through the other rail and experience a repulsive force. As the current through the rails are larger so force exerted on each rail will be large, hence the rail needs to survive this without bending, and must be very securely mounted (1). The force exerted on the rails consists of a recoil force equal and opposite to the force propelling the projectile, but along the length of the rails.

The calculation of the magnetic field is derived from Maxwell's equations in a free space given [11]

$$\nabla x H = J + \delta\Delta/\delta\tau \quad (3)$$
$$\nabla x E = -\delta B/\delta\tau \quad (4)$$
$$\nabla . D = \rho \quad (5)$$
$$\nabla . B = 0 \quad (6)$$
$$B = \mu_o \mu_r H \quad (7)$$

After solving these equations, the stored magnetic field energy can be calculated as

$$E_m = 1/2\int B.\, H\, dv \quad (8)$$

Using the above equations the time varying fields in a space are calculated by finite element analysis technique.

III. Simulation Setup

In general the rail gun is a 3– D device. But assuming that its barrel is infinitely long, the electromagnetic behavior can be analyzed with 2 D finite element models for the cross section of the barrel perpendicular along the longitudinal direction. The cross section of rectangular rail gun is shown in Fig.1.This structure is commonly used in rail gun. Since the structure is symmetric to x – z and y – z planes, only the first quadrant is modeled as shown in Fig2. The total current flow is the same in two conductors, but in opposite direction. The x-axis is an asymmetrical boundary and can be replaced by "odd boundary'' or normal component of the magnetic field intensity is zero (H_n = 0), but the y- axis is a symmetrical boundary and is replaced by "even boundary" or tangential component is zero (H_t = 0).

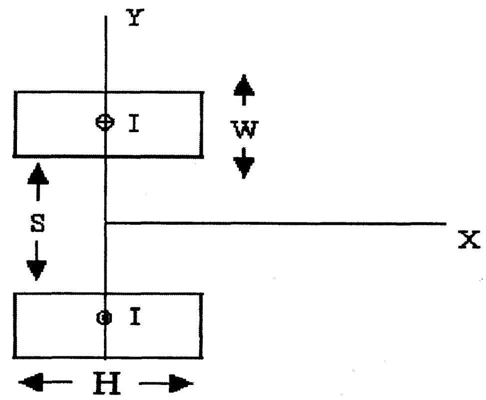


Fig.1. Cross section of Rail gun

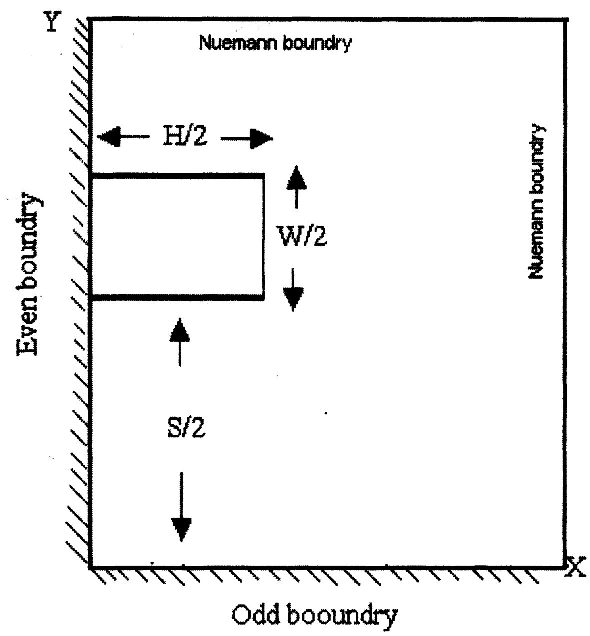
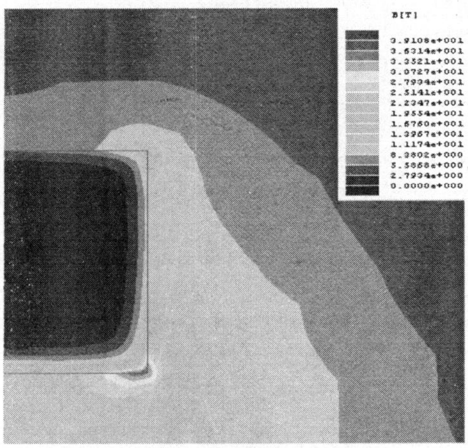


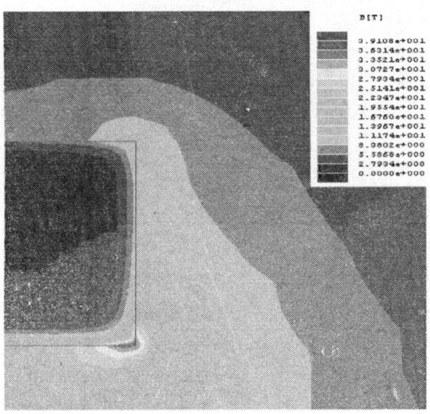
Fig.2. 2-D FEM analysis model

IV. Simulation Result

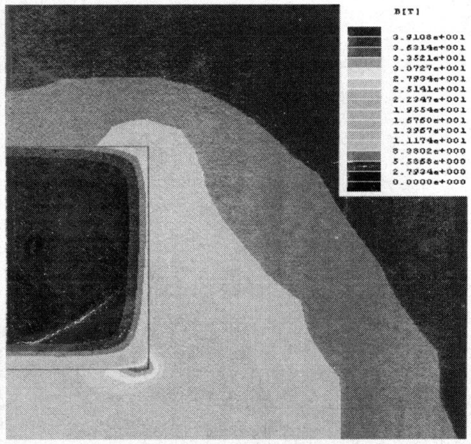
The two-dimensional model for rail gun shown in Fig.2 is used for this finite element method simulation. The rails are assumed to be a copper with conductivity equal to 5.8 X 10^8 S/m and carrying a current of 1MA. Different ratio of rail width to rail separation (W/S) and rail height tovrail separation (H/S) values have been taken for modeling. The maximum current density over a rail cross section , magnetic flux density between the rails, inductance gradient of the rails and repulsive force acting on the rails were computed for different values of W/S and H/S for the rail separation S= 4cm, and S =3cm. The Flux density distribution between the rails and the current density distribution over a rail crosssection for different rail dimensions are shown in Fig 3 and Fig 4. From the figures it is depicted clearly that as the rail width and rail height decreases the magnetic flux density and current density over a cross section increases. Moreover the current is distributed in a very thin layer near the surface of rail edges so this phenomenon produces a hot spot that fuses the rail edges. Hence care should be taken while designing the rail gun. The calculated values of these parameters variation against W/S and H/S are tabulated as shown in Table I and Table II. From the tables it is realized that the value of magnetic flux density, maximum value of current density over a rail cross section, inductance gradient of the rail and rail force increases linearly as the ratio of W/S decreases. In the case of H/S the current density and inductance increases linearly as the ratio of H/S decreases, but in the case of magnetic flux density and force on the rail the value are increases linearly and then start to decrease. The increasing rate of inductance gradient and current density over a rail cross section is higher for the ratio of H/S compared to the ratio of W/S. In the case of magnetic flux density, and force acting on the rail the increasing rate is higher for the ratio of W/S compared to H/S.



[(a) Flux density for W/S=1.0 H=4cm]



[(b) Flux density for W/S=0.1, H=4 cm]



[(c) Flux density for H/S =0.9, W=4 cm]

Fig.3 Magnetic Flux density distribution between the rails

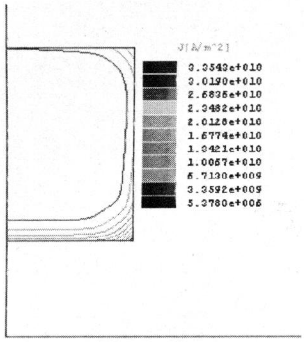
Table I: Rail gun design parameter values against the ratio of W/S

		S= 4cm, H= 4cm				S = 3cm, H = 4cm			
S. No	W/S	L' μH/m	B Wb/m^2	J_A A/m^2 10^{10})	F_r MN	L' μH/m	B Wb/m^2	J_A A/m^2 10^{10})	F_r MN
1	1	0.487	22.27	3.13	3.08	0.430	26.57	3.35	3.84
2	0.9	0.490	22.56	3.18	3.13	0.436	26.89	3.39	3.91
3	0.8	0.497	22.90	3.25	3.2	0.441	27.25	3.45	3.99
4	0.7	0.505	23.27	3.31	3.27	0.448	27.65	3.52	4.07
5	0.6	0.514	23.69	3.38	3.35	0.455	28.10	3.60	4.17
6	0.5	0.525	24.18	3.49	3.45	0.464	28.62	3.709	4.27
7	0.4	0.538	24.76	3.64	3.53	0.474	29.23	3.85	4.39
8	0.3	0.554	25.3	3.81	3.68	0.485	29.97	4.02	4.53
9	0.2	0.573	26.39	4.07	3.83	0.498	30.84	4.34	4.70
10	0.1	0.594	27.1	4.62	4.02	0.510	32.18	4.93	4.93

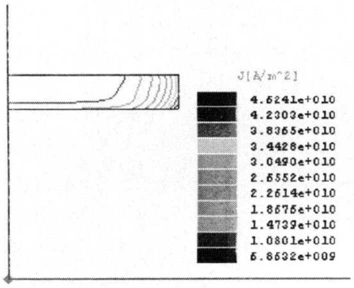
Table II: Rail gun design parameter values against ratio of H/S

		S= 4cm W= 4cm				S = 3cm W = 4cm			
S. No	H/S	L' μH/m	B Wb/m^2	J_A A/m^2 10^{10})	F_r MN	L, μH/m	B Wb/m^2	J_A A/m2 (10^{10})	F_r MN
1	1	0.487	22.27	3.13	3.08	0.469	28.33	3.62	3.77
2	0.9	0.503	22.93	3.27	3.11	0.487	29.11	3.77	3.79
3	0.8	0.525	23.57	3.42	3.13	0.508	29.85	3.98	3.81
4	0.7	0.550	24.48	3.58	3.15	0.536	30.33	4.15	3.82
5	0.6	0.577	25.06	3.78	3.16	0.554	31.17	4.32	3.89
6	0.5	0.607	25.19	3.99	3.17	0.582	31.59	4.55	3.81
7	0.4	0.641	25.5	4.24	3.16	0.612	31.81	4.82	3.79
8	0.3	0.681	25.61	4.58	3.14	0.647	31.74	5.19	3.75
9	0.2	0.728	25.68	5.06	3.10	0.685	31.65	5.67	3.64
10	0.1	0.79	25.12	6.06	3.06	0.727	26.105	7.14	3.56

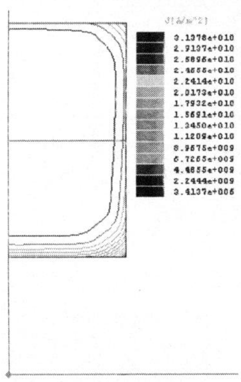
Also it is realized that the value of current density and inductance gradient increases as the rail separation increases but in the case of magnetic flux density and force acting on rail decreases as the rail separation increases. In order to get higher projectile velocity higher ratio of W/S and H/S is selected. But for the lower value of H/S, the flux density and repulsive force are less compare to higher value of H/S. Hence in order to get better performance of rail gun lower value of W/S and higher value of H/S is selected.



D.□. Current density for W/S=1.0 H=4cm.



(b) Current density for W/S=0.1, H=4 cm



(c) Current density for H/S =0.9, W=4 cm

Fig.4. Current density distribution over rail cross section

V. CONCLUSION

This paper investigates the effect of rail dimensions on the current density, magnetic flux density, rail forces and inductance gradient of the rail gun. Models of 2-D finite element simulations are performed for the various values of rail dimensions. It is concluded that as the ratio of W/S and H/S decreases the values of inductance gradient, magnetic flux density, current density over a rail cross section increases. Inductance gradient and maximum current density increases as the rail separation increases in the case of magnetic flux density between the rail and force acting on the rail decreases as the rail separation increases. The increasing value of these parameters is found to be good in the case of decreasing the ratio of W/S when compared with decreasing ratio of H/S.

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