Optimal Utilization of Rail Gun

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Abstract: Railgun is an electrically-powered gun that accelerates a conductive projectile along magnetic metal rails. Various factors increase the projectile velocity. However each method has its own advantages and disadvantages. While increasing the projectile velocity, one has to keep in mind the longevity of the rail guns for practical use also. Railguns are often damaged after few uses due to the extreme working conditions they are subjected to, thus reducing their life span drastically. Some of the problems generally encountered are Velocity Skin effect, Electro migration and flux leakage. We try and provide solutions to some these problems. We also address the theoretical limitation on the current density that is imposed by the melting point of the armature and the gun. All these factors when simultaneously addressed would increase the life span of the rail gun.

Keywords: Armature, Rails, Skin effect, Levitation, Electro-migration.

1. Introduction

The setting up of a rail gun includes the investment of time, money and labor. If the railgun keeps getting damaged after every few uses, it would result in drastic losses. The current research focus is primarily on increasing the release velocity of the projectile [1][2][3]. This paper addresses solutions to the projectile velocity problem at the same time addressing the factors that affect the life span of the gun. The commonly faced problems that result in the damage of the gun are the velocity skin effect [4][5], electro-migration and also deflections between the rails due to high magnetic field [6]. The skin effect is caused due to the sudden spike in the current density at the contact of the armature and the rail gun. This results in the temperature at the vicinity of the armature to go beyond its melting point. The moving armature releases the molten material behind it that destroys the gun making it difficult to re-use the gun.

The paper is organized as follows. Each of the following section addresses a separate problem and explains our proposed technique to overcome the problem.

2. Notations Used

The following notations are used for the different rail parameters throughout this paper.

A=Area of Rails
B=Magnetic Field in Rail gun
a=Length of armature
m_0=Mass of armature
m_r=Mass of each rail.
L=Length of Rails
S_r =Specific heat capacity of Rails
S_a =Specific heat capacity of Rails

3. Use of COMSOL Multiphysics

The setup is shown in Figure 1.The analysis is done on COMSOL using Magnetic Field physics and the model is studied by Frequency Domain analysis at 50Hz.The Figure 1 shows the basic model in COMSOL used to simulate the rail gun. As seen it comprises of two copper rails placed on an Aluminium oxide base. A current density of desired value is passed through a copper contact at the base of the rails and the armature (Aluminium 7075) slides between the rails.

The equations solved in this physics are as follows:

$$(j\omega\sigma-\omega^2\varepsilon_0\varepsilon_r)A+\nabla\times H=J_e \qquad \text{Eqn. 1}$$

$$B=\nabla\times A \qquad \text{Eqn. 2}$$

Where A- Magnetic Vector Potential
H - Magnetic Field Intensity
B - Magnetic Flux Density
J_e - Current Density

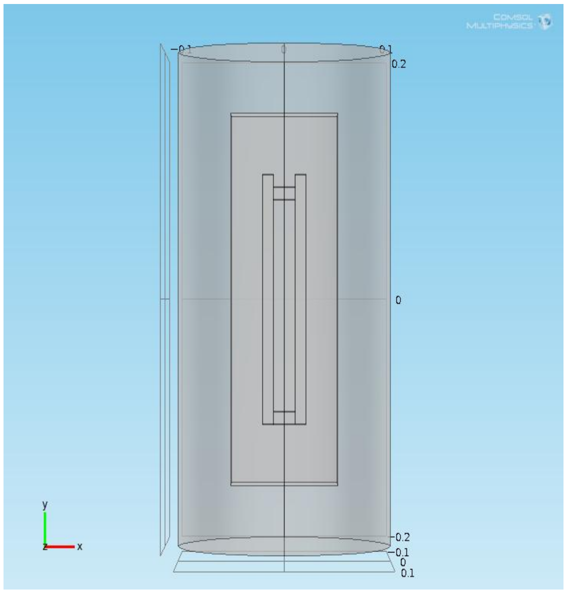

Figure 1: Basic COMSOL Model of a Rail gun. The two rails are placed on an insulated base and the armature moves in the positive y direction.

4. Limitation on current density

In this section we try to find a limitation on the maximum current that could be passed through the rails without the melting of the rails or the armature. The melting point of copper puts a theoretical limitation on this maximum current density. The input energy given to the system is assumed to be dissipated in driving the armature, heat and friction losses. As the melting point of copper is lesser than that of the aluminum, care should be taken to see that the temperature of the system does not exceed the melting point of copper. The length of the rails is assumed to be l_r and that of the armature is l_a, the respective masses be m_r and m_a and the respective specific heat capacities be s_r and s_a .Let the input current i be from a voltage source V. Let the input voltage drive the armature to a final release velocity v at a constant acceleration *a*, the time taken for release being t. Let the temperature change as a result be δθ. The equation for conservation of energy yields (1) where FL is the friction losses.

$$Vit = \tfrac{1}{2} m_a v^2 + 2 m_r s_r \delta\theta + m_a s_a \delta\theta + FL \qquad (1)$$

Using the equations of motions (2) given below with initial velocity *u*=0, we get (3)

$$\begin{aligned} v &= u + at \\ v^2 &= u^2 + 2 a l_r \end{aligned} \qquad (2)$$

$$\begin{aligned} v^2 &= 2 a l_r \\ t &= \sqrt{2 l_r / a} \end{aligned} \qquad (3)$$

Substituting (3) in (1) gives (4)

$$Vi\sqrt{\frac{2 l_r}{a}} = m_a a l_r + (2 m_r s_r + m_a s_a)\delta\theta + FL \qquad (4)$$

Now, the resistance offered to the flow of current by the rails and the armature together assuming they are of same cross sectional area is,

$$R = \frac{(\rho_r 2x + \rho_a a)}{A} \qquad (5)$$

where ρ_r and ρ_a are the resistivity of the rail and the armature respectively and A is the common cross sectional area.

Now the power dissipated can be written as

$$P = i^2 R = i^2 \frac{(\rho_r 2x + \rho_a a)}{A} \qquad (6)$$

It is assumed that Magnetic field is equal along the rails. Let x be the distance travelled by the armature in time t. x can then be written from the equation of motion as follows

$$x = \frac{1}{2}\left(\frac{Bia}{m_0}\right) t^2 \qquad (7)$$

From (5),(6) and (7),the energy dissipated can be written as

$$E = \int_0^{t_0} P dt = \int_0^{t_0} i^2 \frac{(\rho_r 2x + \rho_a a)}{A} dt = \int_0^{L} i^2 \frac{(\rho_r 2x + \rho_a a)}{A} \frac{\sqrt{m_0}}{\sqrt{2Biax}} dx \qquad (8)$$

But the energy dissipated is manifested as a change in temperature of $\delta\theta$ as follows

$$E = (2 m_r s_r + m_0 s_a)\delta\theta \qquad (9)$$

Equating (8) and (9) gives

$$(2 m_r s_r + m_0 s_a)\delta\theta = \int_0^{L} i^2 \frac{(\rho_r 2x + \rho_a a)}{A} \frac{\sqrt{m_0}}{\sqrt{2Biax}} dx \qquad (10)$$

Solving this integral gives a relation between the current density and temperature change as follows.

$$J = \frac{i}{A} = [\frac{\sqrt{2Ba}(2m_r s_r + m_0 s_a)\delta\theta}{\sqrt{Am_0}(\frac{4}{3}\rho_r L^{3/2} + 2\rho_a a L^{1/2})}]^{2/3} \tag{11}$$

Thus, Maximum Current density can be found out by substituting the difference between melting point of copper and the room temperature instead of $\delta\theta$ .From the above calculations, it can be seen that the maximum current density that can be passed through the rails is also a function of the dimensions of the rails. These factors put a theoretical limit on the maximum current density that can be passed through the rails.

5. Magnetic levitation

The rail guns are placed on an insulated base and the armature moves between the rails and on this base. The armature faces a lot of friction from the base during its release that not only slows it down but also results in a wear and tear. To overcome this problem, we suggest the addition of an external magnetic field in the direction of the motion of the armature. This would result in an additional upward force on the armature. The value of the external magnetic field can be so chosen to balance the weight of the armature during its motion. This would ensure that the armature is not in contact with the surface and levitates throughout its motion. The following Figure shows the simulation of the rail gun model in COMSOL to depict the effect of levitation. It is observed that the force exactly balances the weight of the armature for an external magnetic field of strength. The value of the external magnetic field required to balance the weight at a current density of 5x10^{9}A/m^{2} was found to be 5.62x10^{9}T. It can be seen an upward force on the armature is observed that balances out its weight. Figure 2 shows the effect of the variation in Lorentz force with the distance from starting point, for this reason if the armature is in contact with surface then it would lose out much energy. It is thus essential to apply the magnetic levitation for the armature.

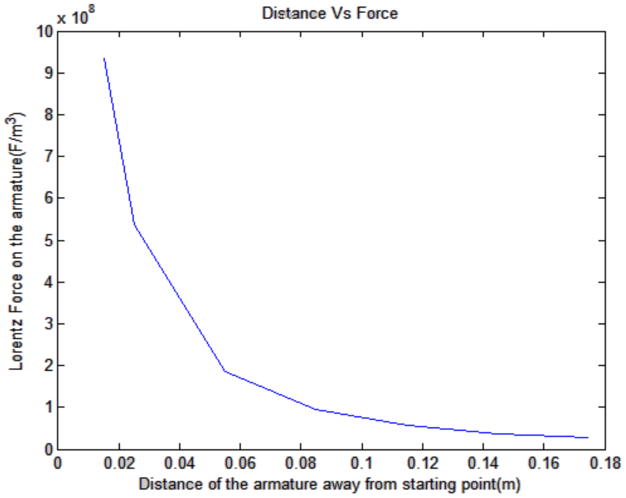

Figure 2: The variation of the Lorentz force on the armature as a function of its distance from the starting point.

6. Velocity skin effect

It is observed that one of the major reasons for causing the damage to a rail gun is the Velocity Skin effect. It is a result of the sliding contact between the armature and the guns. This causes majority of the current to flow in the rear of the armature and also causes non uniform forces on it. These non-uniform current causes an increase in temperature of the armature and this heating results in a structural failure of the setup. The heating also causes the armature to melt in cases where the temperature exceeds the melting point of the armature. The molten armature is released in the rear of the armature on the guns causing damage to the guns and making it difficult for their reuse.

The solution to overcome the problem of skin effect involves the introduction of an additional high resistive layer between the rails and the armature [6][7]. This not only reduces the magnitude of the current flowing through the armature but also removes the contact between conductors which is the main source of the skin effect. The material shown in between the rails and the armature is Titanium, a high resistive material.

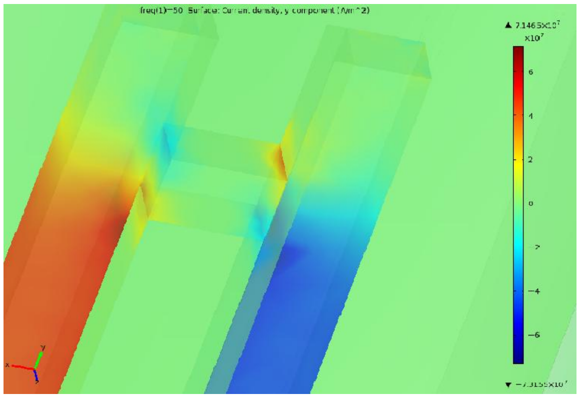

Figure 3: COMSOL depicting Velocity Skin effect

It can be observed from figure 3 that the current density at the contact corners is high. The red and the blue regions at the corners represent high magnitude current densities in the longitudinal direction.

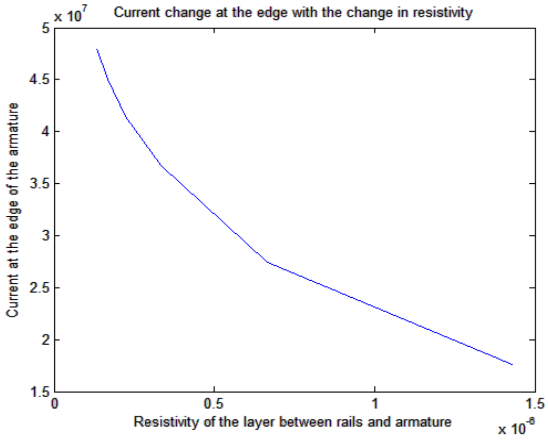

Figure 4: Variation of the current density at the rear of the armature as a function of the resistivity of the additional layer.

It can be observed from figure 4 that as the resistivity of the material increases, the current at the edge decreases thus helps in keeping the current through the edge at a limit. The force on the armature decreases when a resistive material is added between the rails and the armature. This is an indirect implication of the fact that the skin effect decreases on the addition of a resistive material.

7. Electro migration

The rail guns are placed Electro-migration is the transportation of a material caused by gradual movement of ions in a conductor due to the momentum transfer between conducting electrons and diffusing metal atoms. This effect is more significant in applications that use high current densities such as the rail gun. This puts a practical limit on the current density that could be passed through the rail gun without causing structural changes to the rails i.e. without causing electro-migration in the gun. The maximum current density in copper for which there is no electro-migration is found to be $35x10^6 A/m^2$ for a thickness of 35um.

8. Magnetic wrap

To avoid the magnetic field generated in the rail gun to affect the other circuits in the vicinity of the rail gun, we propose the introduction of a magnetic wrap around the rails. This wrap traps all the fields inside itself and does not allow any magnetic flux to pass through it. So the effective magnetic field outside this wrap is very close to zero and the rail gun would have no effect on its surrounding circuits. It can clearly be seen that the field first increases as we approach the center of the gun and finally almost tends to zero as we go outside the wrap. The material for the wrap was chosen as Nickel A because of its low skin depth. As a result the fields are not able to penetrate the thickness of the wrap.

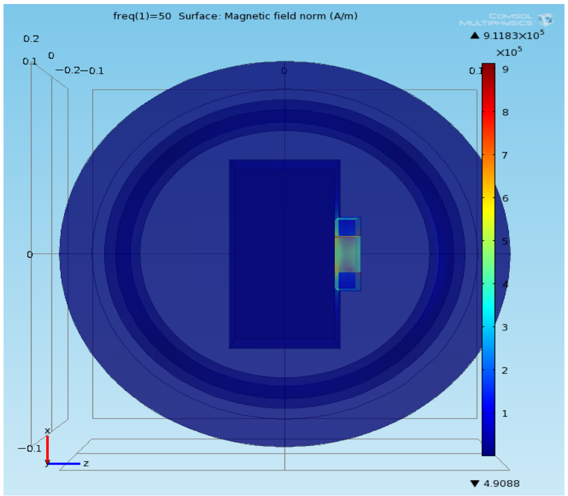

Figure 5: a) The COMSOL result of the simulation of a rail gun showing the variation of magnetic field when a wrap is used.

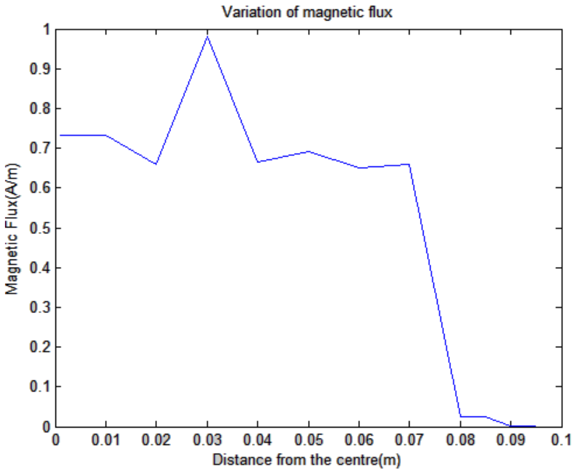

Figure 5: b) The graph depicting the variation of magnetic flux as we move away from the center

9. Conclusions

As already stated earlier the optimal operation of a rail gun should be reached along with increase in the velocity of the projectile. Thus consideration should also be given to other factors that could damage the rail gun. Hence there is a tradeoff between these two factors. One has to choose the rail gun according the application taking in account of the discussed factors.

10. References

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