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A2_8 A portable railgun

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Abstract

In a previous paper we outlined a method for simulating a railgun - a gun based on the principles of electromagnetism. In this paper we assess the possibility of using these same principles to build a smaller, portable weapon akin to a bolt action, high velocity rifle. We find that the concept could theoretically be built but that further research into materials and construction is necessary.

Introduction

In our previous paper on railgun dynamics, we described a computational railgun simulation method for "ideal" railguns - that is, negating heating and frictional effects [1]. Railguns have typically been used on large naval guns to launch high velocity rounds. In this paper we aim to ascertain whether these principles can work on a smaller scale to produce a high-velocity rifle. The advantages of using railgun technology in such an applications are many; cheaper ammunition and adjustable muzzle velocity for example. To begin we must consider what variables we may change to achieve our aim.

Specifications

In order for a railgun to match the performance of a conventional sniper rifle it must offer the same performance in terms of muzzle velocity. The muzzle velocity of the US Army's M40 sniper rifle is 777 m/s [2]. Hence we aim to produce a railgun capable of firing at ≈ 800 m/s. We now set several parameters of the railgun so that we can find the required power. Firstly we set the length of the rails to $l = 0.61$m, identical to the barrel size of the M40 [2]. We then select a rail radius $A = 0.01$m with a spacing of $d = 0.05$m between the centres of the wires. It is important to keep d small compared to l such that the semi-infinite wire approximation that we made will hold [1].

We model the projectile in 2 parts; the conducting part as a cylindrical wire (of radius $a = 0.0025$m) for compatability with our model and one which is a non-ferrous (such that it is not drawn to the rails) mass attached to this wire; forming the bulk of the projectile. We assign this part a mass of 11.3g in keeping with the weight of the 175gr Remmington .308 round [3] used in the M40 [2]. Note that the choice of parameters A, a and d is at this point arbitrary and only done to keep the railgun a reasonable size. A more complex design could alter these parameters to create a more optimal railgun - though this is beyond the scope of this paper. Finally, we must select a material for the construction of our rails and and the conducting part of the projectile. For this we select titanium; on account of its high melting point ($T_m = 1941$ K), heat capacity ($c = 520$ J/kg K at 298.15 K) and strength [5]. The strength of the rails is important since the rails experience a massive force by the same mechanism as the projectile. This choice gives us a resistivity $r = 430 \times 10^{-9}\Omega$ m [6] and a density $\rho = 4510 \text{kg/m}^3$ [5].

With the basic parameters selected, the power requirements of the railgun must be established. We hence used our computational model with these parameters to find an initial capacitor voltage - V_0 - and capacitance (C) that gave the correct value of v_f - the final velocity of the projectile. All simulations begun with the projectile at a distance $x = 0.01$m else due to the $1/x$ dependence of equation 8 in our previous paper [1] the back EMF would become infinite. We find that $V_0 = 267$V and $C = 2$F gives a value $v_f = 797.27$ m/s. We now consider our method of providing this power; a capcactor.

Charging

We begin from the equation for voltage across the plates of a charging capacitor, $V_c = V_b[1-\exp(-t/RC)]$ [4], where t is the time taken to charge the capacitor to voltage V_c, V_b is the voltage the charging circuit, C is the capacitance and R is the resistance seen by the charging circuit. By taking logarithms of both sides and rearranging, we find that$-t = RC\ln(1 - V_c/V_b)$. We note that $V_c \to V_b$ as $t \to \infty$ and hence that the time taken to charge the capacitor to the full voltage required it infinite. It is hence more prudent to consider charging the capacitor to a value very close to V_b and we consider the case $V_c = 0.99V_b$.

To charge the capacitor to the required voltage, a transformer would need to be used since most portable batteries have output voltages far below 267V. We consider a basic transformer system consisting of a primary and seconday circuit. The primary circuit contains the car battery and a coil with N_p turns. The secondary circuit contains a coil of N_s turns and the capacitor. We note that this is an over-simplification of the actual requirements; in reality such a circuit would require an oscillator to produce an AC current in the primary circuit and a rectifier to return the current to DC in the secondary circuit [7]. For the purposes of this simple analysis they are considered negligible. The secondary circuit is where the capacitor charging takes place and hence it is the resistance in this circuit - R_s that we are concerned with. However, there is obviously an effect on charging rate from the resistance in the primary circuit. The effect that this resistance - R_p - has on the secondary circuit is given by $R_{s2} = (N_s/N_p)^2 R_p$. [7]

Hence the total resistance seen by the secondary circuit is

$$R_s = \left(\frac{N_s}{N_p}\right)^2 R_p + R_{s1}, \quad (1)$$

where $R_p = R_w + R_b$, with R_b being the internal resistance of the battery used and r_w being the reistance of the circuit wires. Returning to our capacitor charging, the time taken to charge the capacitor through the transformer circuit from $V_c = 0$ to $V_c = 0.99V_b$ is

$$-t_f = CR_s \ln(1 - 0.99). \quad (2)$$

Assuming that there is a voltage V_f remaining on the plates of the capacitor at the end of each shot, each subsequent recharge then takes

$$-t_s = CR_s\left[ln\left(1 - 0.99\right) - ln\left(1 - \frac{V_f}{V_b}\right)\right]. \quad (3)$$

A procedure for calculating these two equations was added to our previous simulation code. To obtain an estimate of these times, we assume that both primary and secondary circuits consist of only $L = 3$m of copper wire (in actuality this length would depend on the transformer design). Copper has a resistivity of $r = 1.724 \times 10^{-8}\Omega$ m [6] and we assign the wire an arbitrary radius $a_w = 0.0025$mm. The resistance of this length is given by $R_w = rL/(\pi a_w^2) = 0.0026\Omega$. We select a car battery of nominal voltage 12V [8] and internal resistance of $R_b \approx 0.001\Omega$ [9]. Using the voltage and capacitance calculated above, we hence find that the first charge of the capacitor takes 16.44s and each subsequent charge taking 11.52s.

Heating

One of the biggest issues in railgun design is the heating of the rails. The vast currents directed through relatively narrow rails cause a lot of energy to be dissipated by resistance. The normal approach to calculating power dissipated by the resistance of the system (from $P = IR^2$) becomes much more complicated considering that the projectile removes some of this energy in its acceleration. We hence consider basic energy conservation to infer the amount of energy dissipated as heat. The energy of a capacitor charged to voltage V is $E = CV^2/2$ and hence the total loss of energy from our capacitor over the period of firing the gun is

$$\Delta E = \frac{1}{2}C(V_0^2 - V_f^2) \quad (4)$$

This energy is dissipated in two ways; the kinetic energy of the projectile K and the change in heat energy of the system ΔQ such that $\Delta E = K + \Delta Q$. The kinetic energy of the projectile (of mass m and final velocity v_f) is $K = mv_f^2/2$. We now simplify the problem by assuming that the majority of heat energy is dissipated in the rails since they contribute the majority of mass and resistance to the system. The change in temperature caused by the energy change in the rails (of mass M and specific heat capacity c) is $\Delta T = \Delta Q/Mc$. Hence the change in temperature in the rails is

$$\Delta T = \frac{C(V_0^2 - V_f^2) - mv_f^2}{2Mc}, \quad (5)$$

Of course, it is important to remember that resistance is not the only heat source in the gun - there would also be a significant contribution from the friction of the projectile sliding on the rails. This basic thermal model was added to our simulation and using the parameters outlined above, the temperature of the rails after a single shot beginning at standard temperature (298.15K) was found to be 327.54K - far below our quoted melting point for titanium. It appears that the railgun would be capable of a significant number of shots in quick succession without any damage due to this heat.

Discussion & Conclusion

It seems that the physical constraints of a railgun on this scale can be overcome quite easily. We must note that we have not included frictional heating here which for such high speeds will probably contribute a significant amount of heat energy. Thus a material with a high melting point and specific heat capacity is vital. The material must also be strong since the rails are pushed apart by the Lorentz force.

In terms of practicality, the mass of the rails described in this paper is 1.73kg which is easily manageable. However the mass of the selected car battery - 12.73kg - may be problematic from a portability standpoint. The weight of the capacitor array is much higher however - using 15mf capacitors rated to 240v we would require 134 capacitors at a total weight of $\approx$ 200kg [10]. Clearly this is massively impractical for a portable gun. The possibility exists to use higher voltage batteries - Ni-MH cells can provide upto 200V [11] - possibly negating the need for a capacitor bank. Future work should concentrate on the power drain on such a cell.

To conclude, it does seem that a railgun-based rifle is a physical possibility. However, using off-the-shelf components for this task is not possible, and future developments in capacitor and battery technology would be required to make the weight of the system manageable.

References

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