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Linear electromagnetic accelerator

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Abstract

Over time, the weapons have been based on mechanical energy (bows, catapults) and chemical energy (guns, missiles), however, at the moment, more and more weapons are designed using electromagnetic energy (railgun, coilgun). The focus of this paper is to obtain the desired muzzle velocities of a projectile according to the existent current. In the first part of the paper, the railgun and coilgun design are presented along with their most important advantages. Based on these observations, a new design of an electromagnetic launch system is presented. Next, Maxwell interactive software package was used that applies the finite element method (FEM) to analyze and solve 3D electromagnetic field problems in order to analyze the variation of acceleration force, speed in time. All simulation data shows that this design has a great potential, because of the adaptability to different applications.

Keywords: electromagnetic energy, coilgun, projectile, launch system, simulation

1. Introduction

Nowadays, directed energy weapons (DEWs) are nothing new to mankind. They were discovered a long time ago when the famous Greek Archimedes allegedly used polished parabolic mirrors to direct sunlight on the sails of Roman ships while defending the city of Syracuse in order to destroy enemy ships with fire. The device made by Archimedes was used to focus sunlight into approaching ships using mirrors acting collectively as a parabolic reflector, causing them to catch fire.

The US Department of Defense (DOD) defines, in *Electronic Warfare*, a directed-energy weapon as "an umbrella term covering technologies that produce a beam of concentrated electromagnetic energy or atomic or subatomic particles". DEWs are a part of an electronic attack, along with High Power Microwave, Electromagnetic Pulse and Radio Frequency having an important role in the combined operations and destruction of the enemy by combined kinetic and electromagnetic attacks. Also, they use non-kinetic directed energy, which is used as a direct means to incapacitate, injure, kill people, or to incapacitate, degrade, damage or destroy objects.

While DEWs offer a variety of advantages over conventional kinetic weapons including precision, low cost per shot, and scalable effects, there are also some basic constraints, such as beam attenuation, limited range, and an inability to be employed against targets outside the line of sight, which must to be resolved in order to make these weapons effective across the entire spectrum of combat operations.

A representative example which belongs to the directed energy weapons category is the electromagnetic cannon. Electromagnetic cannons use electricity to accelerate the projectile and thus eliminates the danger of explosion of the powder that propels conventional projectiles. Since the fastest and less expensive way to increase the firing range is the speed of the projectile, the electromagnetic cannon is the best choice. With the speed of the projectile, a series of advantages are obtained, such as reducing the flight time to the target and increasing the impact energy, which makes the presence of an explosive load in the projectile unnecessary.

At the time, different designs of electromagnetic cannon were studied: railgun and coilgun.

The most advanced of all projectile acceleration systems using electromagnetic forces is the railgun which can exploit the high kinetic energy stored in the projectile for extremely lethal effects. The name railgun comes from the fact that the system consists of two electrical conductors that also have a guiding role. These two electric conductors are rigidly fixed at a constant distance from each other. The railgun function has an incredibly powerful electric circuit formed by these two rails, which is closed by a mobile conductor that can move along them. This conductor can be the projectile itself or an armature that pushes the projectile.

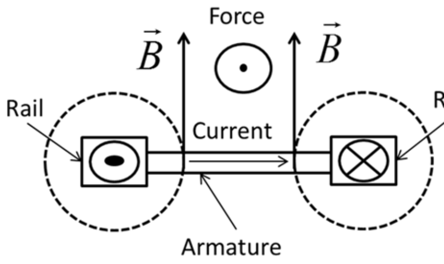

Fig. 1. Railgun

Because this design uses only straight conductors, the value of magnetic gradient inductance is very low. The only way to obtain a high value of force is to increase the current **I** which flows through conductors.

The combination between this simple design and very high currents creates the condition to obtain a great Lorentz force on armature.

$$\vec{F} = \boldsymbol{I} \cdot \vec{l} \times \vec{B} \tag{1}$$

The advantages of this design are:

- the magnetic flux density is perpendicular on armature;
- the current on armature **I** also create the magnetic field around rails.

Even the magnetic field created by rails is not so strong compared with a magnetic field created by a coil, the armature touches the rails and use the magnetic field created very efficiently.

This great advantage comes also with a significant disadvantage of this design: sliding contacts between armature and rails at very high current. For this reason, the rails are damaged after few shots.

Another system that uses electromagnetic energy to accelerate the projectile is the coilgun system. This system is composed of a coil powered by a very high current pulse, of the order of thousands or tens of thousands of amps, in order to create a strong magnetic field using only a fraction of current and avoiding sliding contact, and a projectile. Although the technology of this system dates to 1930, when Northrup professor at Princeton University built the first projectile accelerator at very high speeds, for the moment, the railgun system remains in the spotlight.

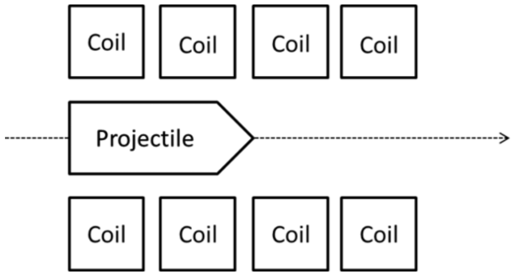

Fig. 2. Coilgun

In order to reduce the value of current *I*, the rails can be replaced by coils. By using coils, we can obtain the same value of magnetic flux density created by the rails with a lower amount of currents. The current inside the armature can be obtained by using induction instead of sliding contacts.

The axial component of magnetic flux density inside coil creates the induced current inside projectile, which interact with radial component of magnetic flux density.

The induced current depends on rate of change of the axial magnetic flux density and the radial magnetic flux density depends on the amount of magnetic flux. The magnetic flux is created by the coil and is the only one which induces the current in projectile, providing simultaneously the radial magnetic field on the induced current.

It is difficult to control with a coil both the rate of change of the axial magnetic flux density and the radial magnetic flux density. Also, it is difficult to control the phase of induced current in projectile and the phase of the radial magnetic flux density.

Compared with railgun, the coilgun creates a strong magnetic field using only a fraction of current and avoiding sliding contacts. The coilgun design is also much more complex than railgun, because the position of projectile must be synchronized with powered coils.

In order to increase the radial magnetic flux density and to decrease the current inside the coil a design with magnetic circuit made by ferromagnetic materials was proposed.

The magnetic circuit also creates a zone where the magnetic field is radial on conductor, in our case, a ring. The E shaped design use the soft magnetic materials and use the Lorentz force to accelerate projectiles, but that design does not allow controlling the difference of phase between induced current in projectile and the phase of the radial magnetic flux density.

$$\vec{F} = I \cdot \vec{l} \times \boldsymbol{\vec{B}} \tag{2}$$

In order to create a great electromagnetic launch systems (EMLS) design, we should preserve the advantages of the railgun design and avoid high currents to obtain the desired force.

The induction coilgun design presented in Fig. 3 is important for our study, because the projectile is not located inside a gun barrel like in a railgun and the classical coilgun, but is located outside the acceleration system. Because we use electromagnetic energy to accelerate the projectile, we do not need a barrel like guns which use chemical energy. This is a very important remark.

If possible, the EMLS should be simple as a railgun and efficient as a coilgun. A design which respects all these conditions is presented in the following chapter.

Before the presentation of a new electromagnetic launch system, we will analyze again the equation of Lorentz force (3).

In order to obtain maximum force, the angle must be $\alpha = 90^0$.

The value of current *I* can be easily increased as we saw in railgun design. The magnetic field density B can be easily created using a pair of coils with magnetic core.

The next element is *l* (length of conductor inside magnetic field) and apparently its value cannot be modified, but if we use more wires (let's say *N* turns), like in a coil, we can easily increase the value of force by *N* times.

If we manage to increase the number of conductors inside the magnetic field by *N* times, we can increase the total force acting on armature by *N* times. This is an easy way to increase the force. This number depends by the size of wire and the space volume where the magnetic field is strong enough to create a useful Lorenz force. The Lorentz force became:

$$\vec{F} = I \cdot \mathbf{N} \cdot \vec{\mathbf{l}} \times \vec{\mathrm{B}} \tag{3}$$

2. Linear electromagnetic accelerator

In this paper, we present the theoretical results obtained during a project aimed to explore the new ways to accelerate a mass using electromagnetic energy. The objective of the project is to accelerate a projectile with a mass of 1 kg from zero to 3000 m/s using 5 meters of acceleration length. According with this objective, the kinetic energy of the projectile is:

$$E_k = \frac{1}{2} m v^2 = 0.5 \cdot 1 \cdot 9 \cdot 10^6 = 4.5 \cdot 10^6 J \tag{4}$$

If we assume the initial speed is zero and the acceleration force acting on the projectile is constant, then the value of the force is:

$$L = E_k = F \cdot d \tag{5}$$

$$F = \frac{E_k}{d} = \frac{4.5 \cdot 10^6}{5} = 900kN \tag{6}$$

Our design consists of a static part which is made by a pair of coils similarly as in Fig. 3. The coils are square with the outer length calculated at a dimension of 180 mm and the inner length calculated at a dimension of 100 mm. The number of turns *N* depends by the size of wire. We are looking for a copper wire able to sustain a fussing current calculated per Onderdonk for 32ms up to 1000 amperes. From the table with American wire gauges, we find AWG 19 with a 0.912 mm diameter. At this dimension of wire, we can accommodate *N* = 4000 turns in the rectangle cross section area obtained from calculations. Since only a single pair of coils is not enough to accelerate the projectile, we will use many pairs which form stages of acceleration. For our simulation we used four stages of acceleration. The length of each stage is calculated at a dimension of 100 mm. These acceleration coils provide the current intensity *I* and the length *l* of conductor inside the magnetic field presented in Equation 3. Because the number of conductors is equal with the number of turns *N*, the Lorentz force will be multiplied by *N*.

Each coil on stage produces an acceleration force so that the total net force on each stage is multiplied by 2.

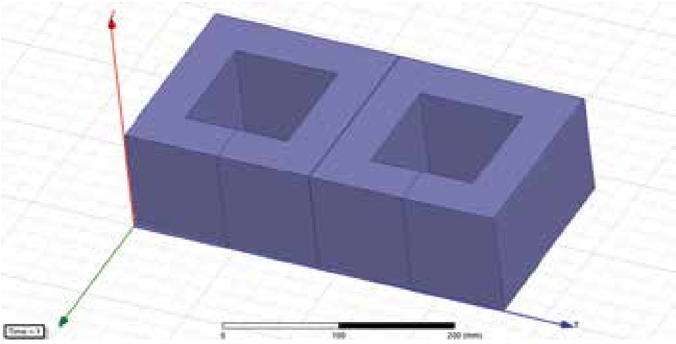

Fig. 3. Static coils for acceleration path

In Fig. 4 we present the two coils made to produce the magnetic Field B required by the Lorentz force. These 2 coils are in front of the acceleration stator. The coils are square with the outer length calculated at a dimension of 180 mm and the inner length calculated at a dimension of 100 mm. The number of turns *N* is 1600. The length of the coils in axe x direction is 40 mm. These two coils are the moving parts. The magnetic field produced by moving coils and the intensity of the current in static coils create an acceleration force in positive z direction.

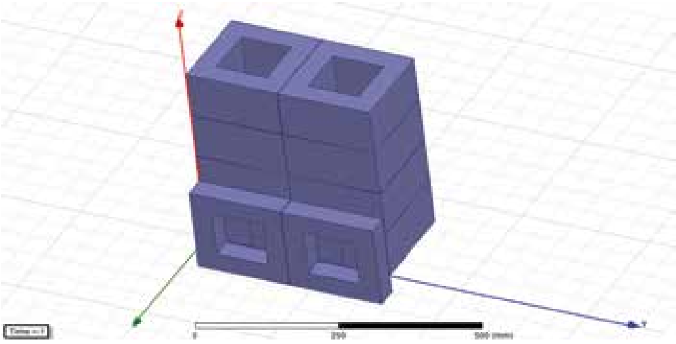

Fig. 4. Moving coils in front of acceleration stages

In order to increase the efficiency of the system, we also created a magnetic circuit made by electromagnetic steel. The shape and position of this core is presented in Fig. 5.

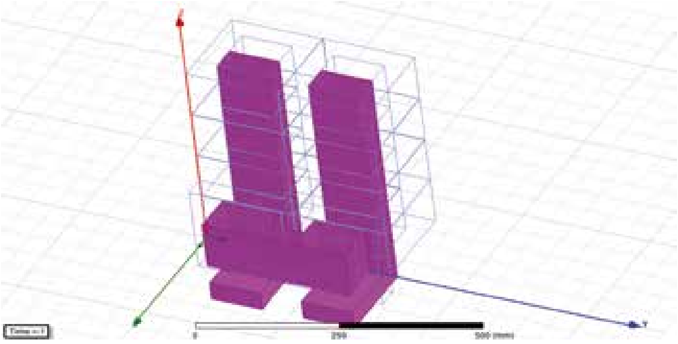

Fig. 5. The magnetic core

The entire design is presented in Fig. 6. The number of acceleration stages can by increased according to need. For our simulations, we used only four stages. We used the same amount of currents to power all of the coils. Because we have moving coils, we can power these coils using moving contacts. This approach is possible because the maximum current used is 1000 A. The acceleration Lorentz force is:

$$F = 2 \cdot I \cdot N \cdot l \cdot B \tag{7}$$

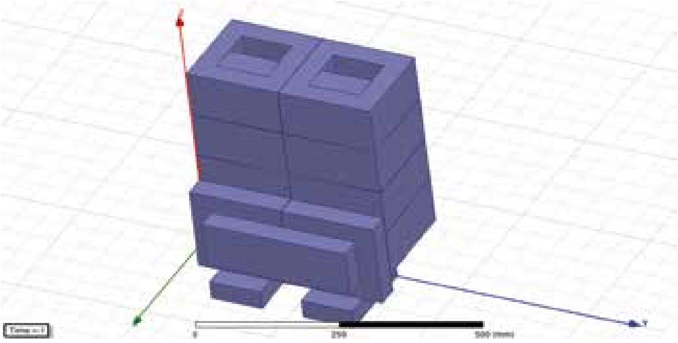

Fig. 6. New EMLS design

3. Simulations

For simulations, we chose the Maxwell interactive software package that uses the finite element method (FEM) to analyze and solve 3D electromagnetic field problems. First, we built the simulation model with the same dimensions as we used to calculate the theoretical values of current intensity *I,* acceleration force *F,* and muzzle velocity *v.* Because the acceleration length is 5 m and our simulations are for only 0.1 m, the value of velocity, we expect from the simulation is 60 m/s.

$$E_k = \frac{1}{2} m v^2 = 0.5 \cdot 1 \cdot 3600 = 1.8\ kJ \tag{8}$$

$$F = \frac{E_k}{d} = \frac{1800}{0.1} = 18\ \ kN \tag{9}$$

According to theoretical calculus, we need a constant force of 18 kN to accelerate a mass of 1 kg from 0 m/s to 60 m/s on a length of 0.1 m. This length is the length of an acceleration stage. We obtained from the simulation the necessary value of current intensity to achieve a speed of 60 m/s is 80 amperes.

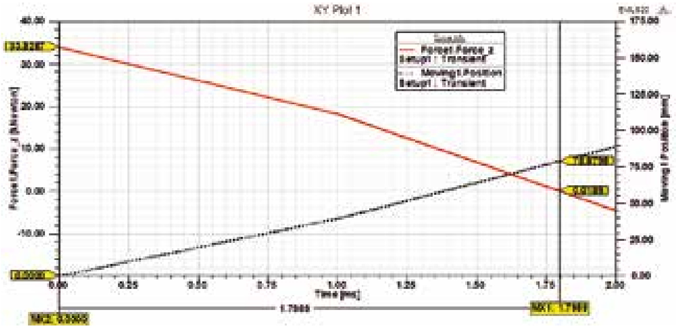

Fig. 7 Variation of acceleration force in time

In Fig. 7, the variation of acceleration Lorentz force in time is displayed with continuous line. As we expected, the force is not constant as in our theoretical calculus. The position of mobile coils in time is displayed with dots. The value of force decreases from 33 kN to 0 N when the mobiles coils reach the point of 78mm. For this simulation, we do not power the stages 2, 3 and 4.

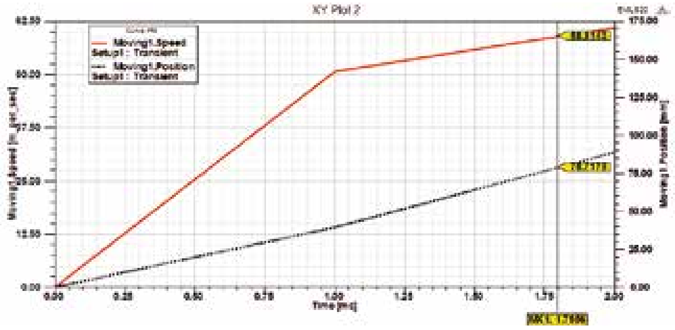

Fig. 8 Variation of speed in time

In Fig. 8, the variation of speed in time is displayed with the continuous line. At the end of first stage after 0.078 m the velocities of mobile coils achieve the value of 58.91 m/s. The position of mobile coils in time is displayed with dots.

According to the results from this simulation, we can predict that the system is able to accelerate a mass of 1 kg from 0 to 3000 m/s on 5m length of acceleration using only 80 amperes current.

4. Conclusion

In this paper, we proved theoretically by means of simulation the possibility of obtaining the desired muzzle velocities of a projectile using a current of 80 A.

The great advantage of this design is its adaptability to different applications. If we need to increase the acceleration force, we can increase the current up to 1000A, but also, we can increase the number of systems. According to the simulation results, this design can be easily used to accelerate projectiles up to 3000 m/s. This system can be an electromagnetic catapult or a coilgun.

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