Exploring Electromagnetic Acceleration of Rail Guns

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(Dated: December 15, 2011)

A simple rail gun was constructed from a pair of aluminum rods and a 0.9 cm diameter aluminum ball as the armature. An array of Neodynium magnets was placed under the rails to create a magnetic field to accelerate the aluminum ball. The amount of current used for the rail gun was small compared to other popular designs, only a maximum of 10 amps was used. The acceleration due to the magnetic field was measured by filming the ball's movement and then analyzing it in Logger Pro and Igor Pro. The velocities of the ball can be found by taking the numerical derivative of the position data, and the slope of v vs t gives the acceleration. The acceleration versus different currents was graphed and it was seen that there is a linear trend between the acceleration and the current. The acceleration based on the current was found for two different sized rails, 1.2 cm and 0.6 cm diameter rails. The rate of change for the acceleration vs the change in current for the 1.2 cm rails was $0.0153 \pm (4.3 \times 10^{-4})\ \frac{m/s^2}{Amp}$ and $0.0355 \pm (2.6 \times 10^{-3})\ \frac{m/s^2}{Amp}$ for the 0.6 cm rails. The theoretical calculation for this rate of change is $0.0467 \pm (9.3 \times 10^{-3})\ \frac{m/s^2}{Amp}$ for the 1.2 cm rails and $0.10 \pm 0.02\ \frac{m/s^2}{Amp}$ for the 0.6 cm rails. The error that is present could be due to assumptions such as the ball rolling on a flat surface instead of between the rails, the magnetic field being narrow, and the length of the armature that current flows through. These assumptions could have a greater impact on the acceleration than what was originally assumed.

I. INTRODUCTION

A rail gun is an electromagnetic accelerator that uses the Lorentz force to propel a conductive projectile, also known as an armature, down a set of conductive rails. The theory that drives a rail gun has been around for quite some time but the best progress in their construction has been within the past half century. The first working rail gun constructed by Joachim Hnsler in 1944 was able to propel a 10 gram mass to a max speed of 1 km/s. However, at the time this was not very impressive considering most chemical propellants were able to accomplish the same speeds. It was not until the development of using a plasma arc from a vaporized metal to propel a projectile that the rail gun concept would be able to surpass chemical propellants.

Although they can reach extreme speeds up to several times the speed of sound rail guns are impractical. The amount of current needed to reach these speeds is huge and can only be reached with giant capacitor banks able to release large amounts of charge rapidly. Rail guns are also self destructive as the friction from their speed deteriorates the rails after each shot. Constant maintenance is required to keep them working. If a way of storing charge more efficiently and reducing the amount the rails deteriorate was developed they could become more practical.

The point behind this paper is the construction of a simple rail gun to gain an understanding of how they work. An attempt to measure the acceleration due to the amount of current supplied to the rails will also be performed to test the theory behind them.

II. THEORY

As charges flow through a conductor they induce a magnetic field that wraps around the conductor. Generally this phenomenon is described for a cylindrical conductor such as a rod or wire. These field lines are represented visually by Fig 1. In the case of a point charge being placed near the current carrying conductor, the resulting fields due to the current would act on the charge. The force that is acting on the point charge is known as the Lorentz force and can be represented as

$$F = q[E + (v \times B)], \tag{1}$$

where F is the force on the particle, q is the charge of the particle, E is the electric Field, v is the particle's velocity and B is the magnetic Field. The second term is the Lorentz force created from the current and is the primary propulsion of a rail gun.

The primary part of the Lorentz force that is propelling the armature is the magnetic field so the equation can be rewritten as

$$F = lI \times B, \tag{2}$$

where l is the total length that the particle travels in the external field.

This is the total force that is exerted on the armature of a rail gun. Fig 2 shows a visual representation of the direction of the force based on the current and magnetic field. The B field represented here is the magnetic field in which the current is immersed created by the Neodynium magnet array. Thus B will be the average of the magnetic field measured from the Neodynium magnet array beneath the rails.

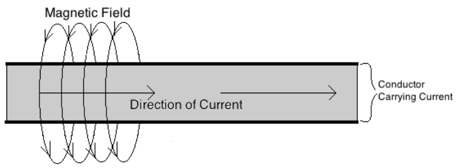

FIG. 1: Current flowing through a cylindrical conductor from an electric field in the direction of the current creates a magnetic field that wraps around the conductor.

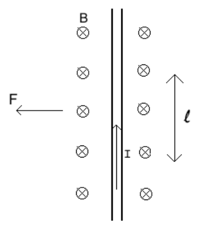

FIG. 2: Lorentz force due to the direction of the current and an external magnetic field.

There is more than one force acting on the armature. The armature being used is a spherical aluminum ball that rolls as the current is applied so there is a rotational force and of course there is always friction. The Aluminum ball achieved very small velocities with the applied current so air resistance is negligible. With the inclusion of these forces the net force can be written as

$$F_{net} = Il \times B - F_{friction} - F_{rotation}. \tag{3}$$

The net force can be changed to mass times acceleration since we are not trying to find the total force of the system but using this to express the motion of the aluminum ball. The Lorentz force can also be used to determine the frictional force at a point where the ball has a constant measured velocity.

The rotational force is the force needed to move the aluminum ball without having it slip and can be derived from the torque needed to rotate the sphere and it's rotational inertia, I_{sphere},

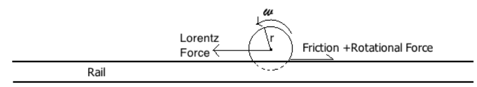

FIG. 3: Visualization of the ball's movement and the forces acting on it as it rolls.

$$F_{rot} \cdot r = \tau = I_{sphere}\alpha. \tag{4}$$

Where τ is the torque, I_{sphere} is the moment of inertia of a sphere ($\frac{2}{5}mr^2$) and α is the angular acceleration of the sphere. By using these equivalents the equation for the rotational force can be rewritten as

$$F_{rot} \cdot r = \frac{2}{5}mr^2\left(\frac{a}{r}\right), \tag{5}$$

where F_{rot} is the rotational force that is needed to move the ball without it slipping, r is the radius of the sphere, m is the sphere's mass and $\alpha = \frac{a}{r}$ is the angular acceleration of the sphere. This equation can be simplified down to the expression

$$F_{rot} = \frac{2}{5}ma. \tag{6}$$

This final representation of the rotational force can then be used in the net force equation to obtain

$$ma = I_1 lB - I_2 lB - \frac{2}{5}ma. \tag{7}$$

Where I_2 is the amount of current needed to keep the ball at a constant velocity. This equation can then be rearranged into something a little easier to work with such as

$$\frac{7}{5}ma = lB(\Delta I). \tag{8}$$

ΔI is used to represent the difference between the current used to accelerate the aluminum ball and the current that causes a constant velocity. One more simplification can be made to obtain

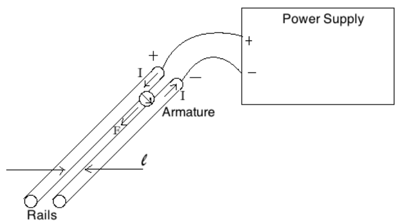

FIG. 4: Basic rail gun design were the armature completes the current flow from the power supply allowing the magnetic force to be created.

$$\frac{a}{\Delta I} = \frac{5}{7}\frac{lB}{m}. \tag{9}$$

This final equation can be used to compare the linear acceleration measured to the length between the rails, its mass and a constant external magnetic field B.

III. CONSTRUCTION

The construction of a rail gun is somewhat simple compared to the physics that governs its performance. The basic components include two long rails and the projectile being fired, also known as the armature. A schematic of a simple rail gun can be seen in Fig 4. The rails and armature need to be a conductive material that permits current flow, generally metals are used for both. The type of metal needed is not specific for a simple rail gun but for optimization of performance a metal that best transfers current while having a low amount of friction between the armature and rails should be used. Silver plated copper rails have been used in rail guns built for pure power along with an aluminum armature.

A rail gun is not complete without a current source. As current flows through the rails a circuit is completed by the armature that is in contact with the rails. The completed circuit creates an electromagnetic force that propels the armature down the length of the rails. Most rail guns use a large capacitor bank as their current source which allows a large amount of charge to be stored then released very quickly. Using a capacitor bank is not mandatory, but they can provide more current than most conventional constant current sources and thus create a larger electromagnetic force. Pure power is not being sought after here so a Hewlett Packard 6282 DC power supply was used as the power source for the rails.

Two different aluminum rod diameters were used for the rails, 1.2 cm and 0.6 cm. An aluminum 1.27 gram

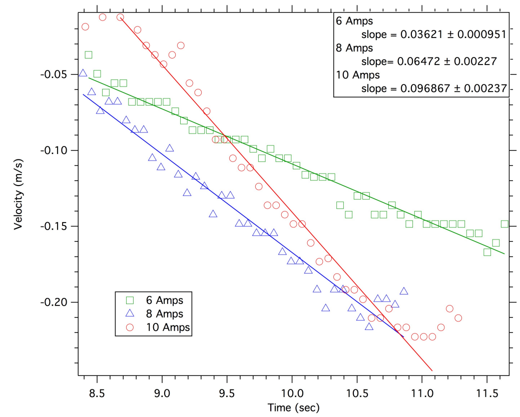

FIG. 5: Numerical derivatives for the position values of the sphere to give the velocity at each position for the 1.2 cm diameter rails. Slope taken over the region that appeared to have the most linear slope. Slope also represents the acceleration of the acceleration of the sphere.

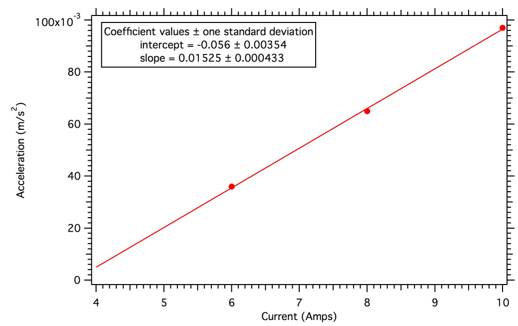

FIG. 6: Acceleration is linearly dependent on the current used for the 1.2 cm diameter rails.

sphere 0.9 cm in diameter was used as the armature because it is light and not magnetic. The total length that the armature traveled on the rails was approximately 35.8 ± 0.1 cm. When the rail gun was first fired up it was noticed that the armature was not moving as ten amps passed through it. The reason for this is that the current source may not be powerful enough to create a large enough electromagnetic field to propel the armature. To fix this an external magnetic field was added by placing a neodymium magnet array under the rails. The external field would help repel the armature more than the current induced field by itself. With this adjustment to the setup the armature was able to travel down the rails as a current was applied.

IV. PROCEDURE

Each of the rods for the rail gun was attached to a terminal of the power supply, one negative the other positive. The aluminum sphere used as the armature was then placed on the rails at the starting mark. Current was ramped up to the desired setting and the armature was given a very small nudge to overcome static friction. The armature rolled down the rails picking up speed till it was stopped by a wooden stop at the 35.8 cm mark. This wooden stop also acts as the separation between both different sized rails, 0.5 cm.

To measure the ball's acceleration, its motion was filmed to be later analyzed in Logger Pro. LoggerPro allows for the motion of the ball to be tracked frame by frame and provide the horizontal position of the ball at a given time based on the film. This process was repeated for both 1.2 and 0.6 cm diameter aluminum rods. The amount of current going into the rods was also changed to see how the acceleration changes as the amount of current changes. The outside magnetic field due to the neodymium magnet array was measured using a Walker Scientific Inc MG-50 Gauss meter. The gauss meter was waved over the area where the ball would be rolling since that is where the strength of the field will be relevant. The measurements were also taken over the center of each magnet as that is where the field would be strongest. The average field strength was $1.66 \times 10^{-2} \pm 1 \times 10^{-4}$ Tesla for the 1.2 cm rods and $3.57 \times 10^{-2} \pm 1 \times 10^{-4}$ Tesla for the 0.6 cm rods. The magnetic field was greater for the smaller rods because the ball's position was closer to the magnets. The field was also not even because of gaps between the magnets and an un-level surface they were lying on.

V. RESULTS

When the rail gun was finally working, the acceleration due to the magnetic force could be measured. This was done by taking a video of the aluminum ball as it rolled down the rails and then tracking its position in each frame with Logger Pro. The data collected from Logger Pro was then further analyzed in Igor Pro. This process was done for two different sized rails, a 1.2 diameter and 0.6 diameter set of rails. Multiple currents were used with these sets of rails to obtain a wider range of accelerations.

For the 1.2 cm diameter rails four currents were used: ten, eight, six, and four amps. As the current was decreased the acceleration of the ball decreased till at four amps it did not make it fully down the rails. From Logger Pro, the position of the ball can be tracked based on a scale set for the program. The camera used to film the movement was placed to where the sphere would not appear to be moving vertically. The scale was set for the total length that the ball moved, measured to be roughly 35.8 ± 0.1 cm. Using Igor Pro the numerical derivative can be taken for the position values to find the velocity at each point. The slope of the velocities for each current is equal to the acceleration of the ball. A graph of the velocities calculated using Igor Pro can be seen in Fig 5. By then graphing the acceleration vs the current with which it corresponds, the acceleration is linearly dependent on the current as seen in Fig 6.

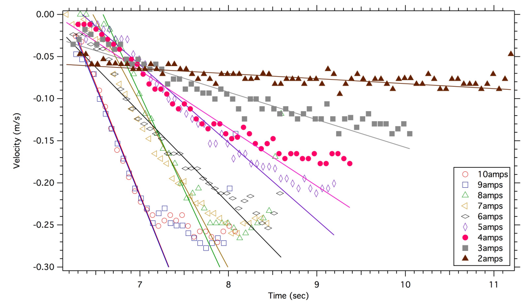

FIG. 7: The numerical derivative for the position of the ball baring gives the velocity at each point for the 0.6 cm diameter rails. Each slope taken over the region of velocities that appeared to have the most linear slope. Slope represents the acceleration for that current setting.

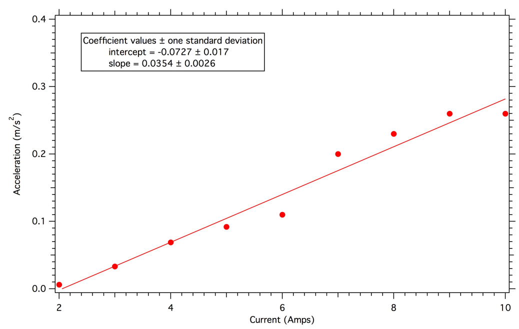

FIG. 8: Acceleration is linearly dependent on the current used for the 0.6 cm diameter rails.

VI. DISCUSSION

To see if the acceleration being measured matches theory, the slope from Fig 6 can be used $(0.0153 \pm (4.3 \times 10^{-4})\ \frac{m/s^2}{Amp})$. This slope represents the change in acceleration over the change in current and can thus be used in equation 9 as $a/\Delta I$. The magnetic field for equation 9 was measured from the Neodymium magnet array and averaged to be roughly 1.66×10^{-2} Tesla. The mass of the aluminum sphere used was measured to be 1.27 ± 0.01 grams. For l the separation between the rods, 5×10^{-3}, was used. With these factored into the right side of equation 9 the result is $0.0467 \pm (9.34 \times 10^{-3})\ \frac{m/s^2}{Amp}$.

The same process can be used with the data from the 0.6 cm diameter rails. For these size rails a larger range of data, starting with ten amps and decreasing by one amp to a minimum of two amps, was taken for more currents to try and obtain better results. The graphs for it can be seen in Fig 7 and Fig 8. It can be seen in Fig 8 that the acceleration is still linearly dependent on the current.

The slope of the acceleration vs the current is 0.0355 $\pm$ 0.0026 $\frac{m/s^2}{Amp}$. Using this the acceleration measured can be compared to the theoretical value using equation 9. The result from this equation using the measured parameters for B (3.57×10^{-2} Tesla), l (.005 meters), and m (1.27×10^{-3} kg) is 0.10 $\pm$ 0.02 $\frac{m/s^2}{Amp}$.

The values that were calculated were based on the assumptions that the sphere is rolling on a flat surface and not between two rails. It is also assumed that the magnetic field from the magnet array encompasses the entire rail gun. This is however not true, the magnet array is more focused because the magnets are not as wide as the sphere itself. So the field strength may be weaker than it should be in comparison to theory. There is also the assumption as to what l is. At the moment l is being measured as the separation between the rails, where it could instead be the distance that the current travels through the aluminum sphere. Based on the sphere and rod's geometries l could be something other than just the separation between the rods. These assumptions could be why the measured values don't match up directly with the theoretical values that were calculated.

It was found that a small rail gun could be made from a pair of aluminum rails, a constant current, and a fairly uniform magnetic field. Two different sized rails were used to create the rail gun. A set of 0.6 cm and 1.2 cm diameter rails. With these rails a small aluminum sphere of diameter 0.9 cm and mass of 1.27 grams was used as the armature for the rail gun. The constant current source being used was from a Hewlett Packard 6282 DC power supply. A constant current source was chosen to be used instead of a capacitor bank because it is easier to determine the amount of current being used from a power supply than a capacitor bank. A Neodymium magnet array was used to propel the armature as the current passed through it.

With these two sized rails accelerations were measured with multiple current values, starting at 10 amps and decreasing down till the ball was no longer able to travel the length of the rails. As the ball rolled down the rails it was captured with a video camera to analyze it's movement in Logger Pro. The data taken with Logger Pro was the ball's position at each frame. The numerical derivative was then taken using Igor Pro to find the velocity of the ball at each position. The acceleration of the ball is the slope of these values when they are graphed. This process was repeated for both size rails and each current used to accelerate the aluminum ball. The accelerations for each current were then graphed vs the current they were present for. This allows for the theory to be tested by using the slope from the graphed accelerations. For the 1.2 cm rails the this slope was 0.0153, and 0.0355 for the 0.6 cm rails. These values were then compared to the theoretical value from equation 9 for the rate at which the acceleration should change based on the current. The theoretical value that was calculated for the 1.2 cm rails was 0.0467 $\pm$ 9.3×10^{-3} $\frac{m/s^2}{Amp}$, and 0.10 $\pm$ 0.02 $\frac{m/s^2}{Amp}$. The error that is present for the measured value based on the calculated value is a factor of three. This error may have been due to assuming the ball rolls on a flat surface instead of between the rods, the magnetic field being narrow, and the length of the length of the armature that the current flows through.

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