# ELECTROMAGNETIC RAILGUN LAUNCHER MODEL TESTING SIMULATION

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## Abstract

The Center for Electromechanics at the University of Texas (CEM-UT) at Austin has developed two simulations for predicting railgun performance while performing research associated with several Defense Advanced Research Projects Agency (DARPA) contracts. The first predicts the electrical performance of the power supply and the electromechanical performance of the railgun. It is capable of modeling a switched homopolar generator (HPG) charged inductive supply, capacitor storage bank pulse forming network supply (PFN), or a combination of the two power supplies. The second calculates the railgun's electromechanical performance using the experimentally measured railgun current.

Test results from CEM-UT's 1-m long, 1.27 cm square-bore, plasma armature railgun have been used to determine the validity of the aforementioned simulations. Deviation between calculated performance and measured performance is typically less than 5% at railgun current levels lower than 500 kA, however at higher currents the deviation increases.

Experimental evidence suggests that the railgun's lack of stiffness and subsequent venting of driving pressure rather than the electromechanical model is primarily responsible for the divergence between predicted and measured results. Additional testing and comparisons are currently being performed with stiffer railgun structures.

# INTRODUCTION

Electromagnetic railgun launcher simulations at CEM-UT predict the electrical performance of the power supply and the electromechanical performance of the railgun. When differences between the simulated results and measured results arose it was difficult to determine whether the electromechanical or electrical model caused the error. In order to test the electromechanical railgun simulation alone a post-shot simulation was written which predicts the mechanical performance of the railgun based on the experimentally measured railgun current.

This paper presents the models used in determining a railgun's performance, the computational method applied to these models and finally a comparison between the pre-shot simulation, post-shot simulation and experimentally measured results.

Test data from CEM-UT's 1-m long, 1.27 cm square-bore launcher was compared to the simulated results. An assembly and cross-sectional view of the 1-m long railgun is shown in figure 1.

# ELECTROMECHANICAL MODEL

## Lorentz Force

The conservative equation of motion in a railgun launcher may be derived by a Lagrangian formulation.[1]

$$\mathcal{L} = T - V \tag{1}$$

where

$T$ = kinetic energy
$V$ = electrical potential energy

and has the observed behavior that

$$d(d\mathcal{L}/d^2x)/dt - d\mathcal{L}/dx = 0 \tag{2}$$

For a typical geometry railgun as shown in figure 2 the energy stored inductively in the rails is:

$$V = 1/2\ L(x)\ I^2$$

where

$V$ = electrical potential energy
$L(x)$ = inductance as a function of length
$I$ = railgun current.

While the kinetic energy stored in the projectile is:

$$T = 1/2\ m\ \dot{x}^2$$

where

$T$ = kinetic energy
$m$ = projectile mass
$\dot{x}$ = projectile velocity.

Substituting T and V in equations 1 and 2 yields:

$$m\ddot{x} - 1/2\ I^2\ dL/dx = 0$$

which may be rearranged to the more familiar form:

$$F = 1/2\ L'\ I^2 \tag{3}$$

where

$F$ = force on the projectile
$L'$ = inductance per unit length.[2]

## Thermodynamic Force

When a metallic foil is used to initiate a plasma armature in a railgun it imparts a thermodynamic force on the projectile caused by expanding hot gases as it explodes. Experimental evidence indicates that this effect may be accounted for by giving the projectile an initial velocity of 400 m/s in pre-shot simulations. This value was chosen from the average values of the y-intercept of post-shot plots of the integral of current squared vs. measured velocity. In post-shot simulations the observed intercept for each particular shot is used instead of the average value.

Frictional Force

Current CEM-UT railgun simulations account for frictional losses only. To compute frictional losses the pressure as a function of position in the projectile is determined. A force normal to the railgun bore is calculated from the pressure distribution and then multiplied by a velocity dependent friction coefficient to yield the frictional loss. Ablation and viscous drag are not incorporated into the present simulations because good correlation is achieved without them; however, they can be added later when experimental results indicate the need for them.

The biggest loss mechanism not currently modeled is caused by deflection of the railgun structure and subsequent venting of plasma. This single effect is the most detrimental to present CEM-UT railgun performance.

To determine the frictional loss, the pressure normal to the gun bore is necessary. The pressure in the projectile is assumed to be linearly distributed, starting with the Lorentz force divided by the base area at the back of the projectile and being zero at the front surface. The pressure as a function of axial position is multiplied by the projectile side area as a function of axial position to account for various projectile geometries and then integrated to derive the projectile force normal to the bore as a function of position as shown in figure 3. The effect of Poisson's ratio is included later since it is a constant and unaffected by the integration.

The projectile is loaded on three axes so Poisson's ratio may not be used directly to calculate the stress on the bore due to the projectile drive pressure. Shigley[3] defines the triaxial stress state as when none of the three principal stresses are zero as shown in figure 4. The principal strains are:

$$\epsilon_1 = \sigma_1/E - \mu\sigma_2/E - \mu\sigma_3/E$$

$$\epsilon_2 = \sigma_2/E - \mu\sigma_1/E - \mu\sigma_3/E$$

$$\epsilon_3 = \sigma_3/E - \mu\sigma_1/E - \mu\sigma_2/E$$

where

$\epsilon$ = the respective principal strain
$E$ = the modulus of elasticity
$\sigma$ = the respective principal stress
$\mu$ = Poisson's ratio.

Rearranging, the principal stresses are:

$$\sigma_1 = (E\epsilon_1(1 - \mu) + \mu E(\epsilon_2 + \epsilon_3))/(1 - \mu - 2\mu^2)$$

$$\sigma_2 = (E\epsilon_2(1 - \mu) + \mu E(\epsilon_1 + \epsilon_3))/(1 - \mu - 2\mu^2)$$

$$\sigma_3 = (E\epsilon_3(1 - \mu) + \mu E(\epsilon_1 + \epsilon_2))/(1 - \mu - 2\mu^2).$$

If the projectile is confined along axes 2 and 3, as is the case in a square-bore railgun, then:

$$\epsilon_2 = \epsilon_3 = 0$$

and the principal stresses are:

$$\sigma_1 = (E\epsilon_1(1 - \mu))/(1 - \mu - 2\mu^2)$$

$$\sigma_2 = \sigma_3 = (\mu E\epsilon_1)/(1 - \mu - 2\mu^2).$$

Rearranging and substituting yields $\sigma_2$ and $\sigma_3$ in terms of $\sigma_1$:

$$\sigma_2 = \sigma_3 = \mu\sigma_1/(1-\mu). \tag{4}$$

Due to the triaxial loading of the projectile the von Mises stress is computed in order to determine if the projectile has exceeded its yield strength. Shigley defines the von Mises stress for a triaxial state as:

$$\sigma' = (((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2) / 2)^{1/2}$$

where

$\sigma'$ = the von Mises stress.[4]

Substituting:

$$\sigma_2 = \sigma_3 = \mu\sigma_1/(1-\mu)$$

yields

$$\sigma' = \sigma_1(1-2\mu)/(1-\mu). \tag{5}$$

To determine if the projectile has yielded, the von Mises stress instead of the pressure on the base of the projectile is compared to the yield strength of the projectile material.

During the simulation the yield position of the projectile is calculated and used to find the normal side force in the projectile for the yielded and unyielded regions. The total normal force per side is determined by individually substituting the unyielded and yielded normal force for $\sigma_1$ in equation 4 (since equation 4 merely scales it may be applied to either pressure or, as in this case, force) and using Poisson's ratio for $\mu$ in the unyielded case and 1/2 for $\mu$ in the yielded case then summing them together. Using the same approach the frictional loss can be adjusted to account for various obturator styles and projectile configurations. A velocity dependent friction model is then applied to the total normal side force to determine the loss in projectile drive.

A velocity dependent frictional model is used based on work done by Bowden and Tabor[5] such that:

$$\eta = AV^{-B}$$

where

$\eta$ = the velocity dependent friction coefficient
$V$ = the velocity in feet per second

A = a constant scale factor
B = a power factor

Bowden and Tabor's work was done sliding nylon on steel where they found coefficient B to be -0.4. In work published by Powell and associates it was assumed that B was the same as in Bowden and Tabor's work but A was scaled by the ratio of the static coefficient of friction of Lexan on steel and nylon on steel yielding A to be 4.0. Powell states that, "This approach produces a realistic trend and reasonable values but is known to be approximate."[6] Since a variety of materials are used in railguns the equation has been rewritten to eliminate the scaling done by Powell, dividing A by the static coefficient of friction for polycarbonate on steel and introducing the coefficient of friction of the projectile material on the bore, and altering the values A and B to better fit the data such that:

$$\eta = 3.8(\eta_1/\eta_2)V^{-.437}$$

where

$\eta$ = the velocity dependent friction coefficient
V = the velocity in feet per second
$\eta_1$ = the static coefficient of the projectile on the bore
$\eta_2$ = the static coefficient of the polycarbonate on steel.

In CEM-UT railgun simulations the force normal to the bore is multiplied by the velocity dependent friction coefficient to determine the loss in driving force. A check is performed to insure that the frictional loss does not exceed the drive force and in the event that it does a message is printed to the screen indicating to the operator that it has. Table 1 lists the static coefficients of friction for materials used in CEM-UT railguns as determined in CEM-UT labs.

**Table 1.** Static coefficients of friction of polycarbonate on various bore materials.

| Bore Material | Coefficient of Friction on Polycarbonate |
|---|---|
| Steel | .23 |
| Copper 110 | .34 |
| Quartz Glass | .22 |
| Plasma Sprayed Molybdenum | .24 |
| 40% Glass Filled Polycarbonate | .68 |

## COMPUTATIONAL METHOD

Two different simulations were written in Fortran. The first predicts the electromagnetic performance of the electric circuit and the railgun together, while the second predicts the railgun performance based on the measured gun current after a test. The Lorentz force and the velocity dependent friction model is incorporated into both of them. The first simulation was developed to predict the behavior of an upcoming test so that the timing of the various system components could be determined and hereafter will be referred to as the pre-shot simulation. The second simulation was developed to check the electromechanical model used in the railgun and hereafter will be referred to as the post-shot simulation.

### Pre-shot Prediction

In order to understand the performance of the railgun, realistic system simulations have to be designed. Such simulations have been under development at CEM-UT for seven years. The simulations include empirical results derived from experiments conducted over the past 14 years. Examples of the modeling parameters are the excitation flux change in iron-core HPG's as a function of discharge current: the empirical treatment of the sliding electrical contacts in rotating machines, brush friction, and brush voltage drop; the empirical treatment of the frictional force produced by hypervelocity projectiles sliding on both rail and insulator surfaces; and the experimental railgun inductance gradient (L') measured from actual railgun performance which then allows identification of static measurement techniques or theoretical calculations to determine L' for other railgun geometries and materials. These simulations are used to set up hypervelocity impact experiments, to determine timing for photographing projectiles in flight, and to identify loss mechanisms that may be present in the railgun.

The present simulation is a lumped element circuit model that is solved using a 7th order Runge Kutta integrator with automatic time stepping. The circuit parameters are values measured at frequencies close to those that occur in an actual railgun event. The first simulation allows up to 10 capacitor banks to be switched on with a variable time delay between each discharge ( see figure 5.). The railgun event begins by exploding a conductive fuse behind a stationary projectile. The models of Bealing and Carpenter[7] are used to determine the fuse impedance at early times. When the fuse has made the transition to the vapor state the voltage across it is artificially ramped to an experimentally observed arc voltage where it is held for the duration of the test. The Lorentz force less the previously mentioned frictional force drives the projectile. During the on state all ignitron switches are modeled as a constant 50-V drop. In addition, a breech crowbar model has been incorporated into the simulation. Generally the activation of the crowbar is after the railgun event and is to prevent arc damage from occuring at the end of the gun. It is included in the simulations so that operating conditions of the crowbar can be established and thereby incorporated into the switches' design. Finally, at each time step an energy balance is performed to insure that numerical instabilities are not causing errors.

In the second simulation the HPG is modeled as a magnetic flux and speed-dependent voltage source. Coupling between the electrical and electromechanical circuits is accomplished by the following expression which relates torque to discharge current:

$$T = \phi I / 2\pi$$

where

$T$ = Rotor torque
$\phi$ = HPG excitation flux
$I$ = HPG discharge current.

An empirically derived, non-linear function is used to model the behavior of the opening switch resistance in the simulation. The HPG circuit is shown in figure 6. Another change from the lumped sum model used in the first simulation is a trapped flux model for the energy storage inductor. Also accounted for in the simulation is the heat lost in the coil conductors during a fast transient discharge due to the diffusion of magnetic energy. A mechanical torque term is added to the electromechanical expression to account for the frictional brush drag on the HPG rotor. The sliding interface voltage drop at the brush rotor interface was determined experimentally and is modeled as a current dependent voltage source. The railgun model is the same as used in the capacitor and at each time step an energy balance is performed to check the numerical solution.

To stage the capacitors with the homopolar generator the HPG code is run until switching is complete, after which the homopolar is modeled as capacitor discharging and is inserted into the capacitor simulation code.

At CEM-UT the only acceptable verification of the railgun performance is a dual exposure flash x-ray picture of the projectile in flight. Presently a continuous x-ray fence is being designed to trigger the flash x-ray when the projectile is in front of the flash x-ray heads. Until the x-ray fence is developed the simulations are the only tools available to predict when the projectile will pass in front of the flash x-ray head. To date several flash x-ray pictures have been made of projectiles in flight which is testament to the accuracy of the pre-shot simulation. Plans for the future include more realistic plasma model and data reduction code to help identify the electrodynamic behavior of the railgun.

## Post-shot Prediction

A post-shot no-loss velocity prediction based on the measured railgun current is achieved by integrating the acceleration from the Lorentz force. This prediction is an excellent tool to reduce the difficulty of determining a railguns performance when power supply anomalies occur that are not modeled in the pre-shot simulation. For the post-shot simulation to be believable the current in the railgun must be measured accurately. Presently, Rogowski coils and integrated current measuring probes that are used to measure the railgun current are calibrated with a current viewing whose resistance is known within 0.4%. The predicted velocity including losses is calculated using the no-loss prediction and applying the velocity dependent friction model to determine the loss in driving force. The difference between the Lorentz force and the frictional force is used to determine the acceleration, which is integrated to achieve the velocity including losses. A second iteration is performed using the first veloctiy with loss to predict the frictional loss. Iterations are continued until the convergence criterion set by the user is met for all data points. Typically less than five iterations are required for all velocity data points to converge within 1 m/s.

Shot parameters required for the prediction are: projectile dimensions and material specifications, measured railgun current, railgun inductance gradient, thermodynamic velocity, ailgun length, and static coefficients of friction. A user option allows the input of measured projectile exit time to print predicted velocity at that point.

Currently, the post-shot Fortran code is being run on a VAX 11/750 computer that CEM-UT uses primarily for data aquisition and reduction. Future plans include incorporating pre-shot code and inductive railgun probe interpretation code onto the same computer which will reduce the labor involved in transferring data from one computer to another when plotting results.

## COMPARISON OF RESULTS

Measured data, pre-shot prediction data, and post-shot prediction data for velocity and position for five, 1-m long railgun tests and one, 2-m long railgun test were compared. Tests presented were chosen on the basis of completeness of measured test data. Measured data was obtained using the methods discussed by Cook.[8] On all of the shots presented, measured velocity and position, pre-shot prediction without loss velocity and position, pre-shot prediction with loss velocity and position, post-shot velocity without loss, and post-shot with loss velocity and position are plotted. On 1-m long shot #15 a comparison between measured and predicted gun current is included.

### 1-m Shot #15

During test #15 of the 1-m long square-bore railgun a 1.8-g projectile was accelerated to 4.5 km/s as measured by CEM-UT's flash x-ray system. Quartz glass insulators and copper 110 rails lined the bore of the gun. The capacitor storage banks were sequenced to produce a steadily rising current profile through the shot with the peak value rising to 420 kA.

Figures 7 and 8 represent the velocity and position of the projectile. Both the pre-shot and post-shot predictions track the projectiles position accurately with no more than 5% error at any time. Both predictions that include losses predict the exit time of the projectile within 10 $\mu$s of the measured exit time. The velocity measurements depict a variance of about 5% through the shot. As expected, the simulations without loss exited sooner and/or with higher velocities than did the simulations with loss. Upon disassembly the railgun seals appeared clean thus, indicating little plasma leakage.

Figure 9 represents the gun current on shot #15. It is clear that the actual gun dynamics are not completely represented by the model used in the pre-shot simulation. At early times during the shot the armature resistance is a function of the resistive heating that occurs due to the gun current, later in the shot the armature is represented by a constant 450 V drop. Until enough energy has been deposited into the armature to cause it to vaporize the projectile position is fixed. As a result of the projectile being staionary the gun impedance in the simulation is lower than in actuality thus causing the gun current to be higher. Later in time the 450-V drop across the armature does not represent the actual armature drop and thus introduces more error. Future plans include incorporating a dynamic armature model into the pre-shot simulation.

### 1-m Shot #16

During test #16 of the 1-m long square-bore railgun a 1.7-g projectile was accelerated to 4.75 km/s as measured by "make" style velocity screens. Forty percent glass-filled polycarbonate insulators and plasma sprayed molybdenum on copper rails lined the bore of the gun. The capacitor banks were sequenced to produce a steadily rising current profile with a peak value of 450 kA.

Figures 10 and 11 represent the velocity and position of the projectile during shot #16. As in the previous shot the pre-shot and and post-shot predictions track the position of the projectile accurately, however note that the affect of the higher coefficient of friction due to the polycarbonate sidewalls causes the pre-shot prediction without loss to be in error by as much as 9%. The velocity measurements depict a variance of about 10% through the shot. Note the excellent correlation between measured velocity and predicted velocity with losses. Once again predictions without losses exit sooner and/or with higher velocities. Upon disassembly the railgun seals appeared clean, indicating little leakage.

1-m Shot #19

Shot #19 of the 1-m long square-bore railgun accelerated a 2-g projectile to 5.1 km/s as measured by the flash x-ray. Quartz glass insulators and copper 110 rails were used to line the bore of the gun. The capacitor stores were discharged to produce a quickly rising current profile that peaked at around 580 kA. Throughout all but the first 100 μs the current was above 500 kA.

Figures 12 and 13 represent the velocity and position of the projectile during shot #19. During the first 100-150 μs the simulations tracked the position of the projectile well, however, soon thereafter performance was reduced below that of the simulation. The result was a deviation in performance of approximately 10% position wise and about 20% on the velocity.

Disassembly of the railgun revealed carbon soot staining of the bore seals and small craters in the insulators in the magnetic current measuring probe areas. Close inspection of the current measuring probe cavities revealed black soot indicating leakage.

1-m Shot #20

Shot #20 of the 1-m long square-bore railgun accelerated a 1.9-g projectile to 3.8 km/s as determined by current measuring probes. Forty percent glass-filled polycarbonate insulators and plasma sprayed tungsten on copper rails lined the bore. A switched homopolar generator/inductive power supply produced a peak gun current of 350 kA.

Figures 14 and 15 represent the velocity and position of the projectile during shot #20. During the early part of the shot the measured and simulated data match well; however at 300 μs the data started to diverge. Since the railgun seals were clean it is suspected that plasma leakage was not the cause. Disassembly of the railgun revealed extensive damage to the tungsten coating on the last 50 cm of the rails. This damage included chipped out sections in places which may have been responsible for the poor correlation at later times during the shot. In addition, since none of the downrange diagnostics performed correctly, an accurate muzzle velocity was not obtained.

1-m Shot #24

Shot #24 of the 1-m long square-bore railgun accelerated a 2-g projectile to 5.9 km/s as determined by the flash x-ray system. Quartz glass insulators and plasma sprayed molybdenum on copper rails lined the bore. A switched homopolar generator was staged with capacitor stores to produce a peak current of 700 kA. A new frame structure was incorporated which increased the stiffness of the gun over previous tests.

Figures 16 and 17 represent the velocity and position of the projectile during shot #24. Due to space limitations fewer magnetic probes could be incorporated into the design thus eliminating the smoothness of the plotted data. Timing errors in store setup caused the first store to fire while the homopolar opening switch was still commutating current into the railgun, producing a condition that could not be modeled accurately with the present simulation. Because of the stiffer gun structure it was deemed necessary to include this test in the paper. With the all the aforementioned problems the simulation still maintained a correlation of within 15% in position and 10% in velocity. Disassembly of the railgun revealed some evidence of leakage but for the most part the railgun seals were soot free.

### 2-m Shot #4

Shot #4 of the 2-m long square-bore railgun accelerated a 2.2-g projectile to 4.7 km/s as measured by "make" style velocity screens. A switched homopolar generator was staged with the capacitor stores to produce a peak current of 680 kA.

Figures 18 and 19 represent the velocity and position of the projectile during shot #4. Correlation of measured and simulated data was good during the first meter of the railgun, however when the gun current rose above 500 kA during the second meter of the railgun, correlation between measured and simulated data diverged rapidly.

Upon disassembly the second meter of the gun seals were covered with carbon soot indicating plasma leakage. Typically, quartz glass insulators are destroyed by the pressure of the plasma armature, however no breakage was observed during the second meter of the gun.

## CONCLUSIONS

Two railgun performance simulations were written that include frictional loss models. At levels below 500 kA the correlation between measured performance and predicted performance is typically better than 5%. At current levels exceeding 500 kA experimental evidence suggests that CEM-UT's current railgun lacks the stiffness required to contain the pressure generated by the plasma armature and consequently vents driving pressure, spoiling the performance. Currently, structural changes are being incorporated into the railguns design that will increase the gun's stiffness. The armature model currently used is not complete. Future work will incorporate a dynamic armature model into the pre-shot simulation. Once these modifications have been made the shot results and shot predictions will be compared and a determination will be made as to whether ablation and viscous drag models need to be incorporated into the prediction models.

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