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Technical Report ARFSD-TR-90028

BASIC SIMPLE MODELING OF IN-BORE MOTION OF RAILGUN PROJECTILES

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July 1991

US ARMY
ARMAMENT MUNITIONS
& CHEMICAL COMMAND
ARMAMENT RDE CENTER

U.S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Fire Support Armaments Center

Picatinny Arsenal, New Jersey

REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE July 1991	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE

BASIC SIMPLE MODELING OF IN-BORE MOTION OF RAILGUN PROJECTILES

5. FUNDING NUMBERS

6. AUTHOR(S)

Szu Hsiung Chu

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Electric Armaments Division (SMCAR-FSE)
Picatinny Arsenal, NJ 07806-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

Technical Report ARFSD-TR-90028

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ARDEC, IMD
STINFO Br
ATTN: SMCAR-IMI-I
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

This is the first of three basic reports on in-bore balloting motion of a projectile launched in an electromagnetic railgun.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

In an electromagnetic (EM) railgun a projectile encounters a complex force environment during launch. A thorough understanding of these forces is critical to projectile and gun tube design. There are many parameters involved and interacting relationships which must be determined. To better understand and establish the in-bore force models, we begin with a basic simple model which computes only the axial motion. More complicated models will be introduced in subsequent reports which will include lateral forces and gun tube vibration effects.

This report deals with a very simple axial motion model. Only the effects of the propulsion force, projectile package mass, air resistance, and the friction forces are presented. Equations of motion are derived and solved. A sample computation with available data is performed and curves plotted to give clearer understanding of the results.

14. SUBJECT TERMS

In-bore motion Balloting Gun dynamics Projectile Railgun

15. NUMBER OF PAGES 15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-1 298-102

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INTRODUCTION

A previous study of projectile in-bore motion in electromagnetic railguns (ref) concluded that in-bore motion affects the lateral impact of the projectile on the barrel, muzzle jump, intermediate and terminal ballistics, and consequently the accuracy of hitting the target. Lateral forces also affect the contents of the projectile such as its electronic package. The force structure and in-bore projectile dynamics are an important concern in the development of an armament system for an electromagnetic launcher. In addition, unlike for a conventional gun, the circumferential construction of the barrel is not uniform, complicating the analytic work.

To make the problem easier to understand, it was decided to analyze the problem on several levels. Beginning from the basic simple model which computes only the axial motion, more complicated models will be introduced to include as many lateral forces and gun tube vibration effects as possible. This is the first of three basic reports documenting the in-bore forces acting on the electromagnetic railgun projectile.

Only the axial motion of the projectile package inside the barrel is considered in this report. The analysis is simplified by ignoring many complicated effects, such as the compression effect of the projectile, barrel expansion, gun vibration, thermal effect, and the rotational motion and related effects. The propulsion force is assumed to be a known quantity. The friction force between the projectile package and the barrel is included. The effect of armature and projectile weights and the drag force of air resistance are considered. Consequently, the equations of motion are formulated by considering the projectile in a linear dynamic equilibrium under the action of the abovementioned forces.

The solutions to the derived equations are obtained by either closed form or numerical methods. The first step is to compute the acceleration versus time profile. After this, velocity and travel down the rails are obtained by the integration technique. This gives a basic knowledge of the in-bore motion.

Sample calculations are given with the available data. Figures are included to show projectile displacement, velocity and acceleration as a function of time.

DISCUSSION

Assumptions

The projectile and the armature are assumed to be integrated into one projectile package. The propulsion force is applied uniformly to the rear face of the armature, so that its resultant is acting at the armature base center. It is coinciding and directed along the barrel centerline as is the mass center of the projectile package. All components such as the barrel, projectile and armature are considered rigid bodies.

The axial components of the resultant forces of friction, projectile package weight, propulsion force and air resistance are considered to act along the barrel centerline, since only the axial linear motion is analyzed. The resultants of the forces normal to the barrel centerline and their moments are ignored. The normal motion and rotation are, therefore, not considered in this simple basic model.

Governing Equations

From the above-mentioned conditions equations of equilibrium are derived from forces along the x-axis which is also the centerline of the barrel. The projectile package, the rails and the resultant acting forces are shown in figure 1. The x-axis or the barrel may have an inclination angle, α, with respect to the horizon.

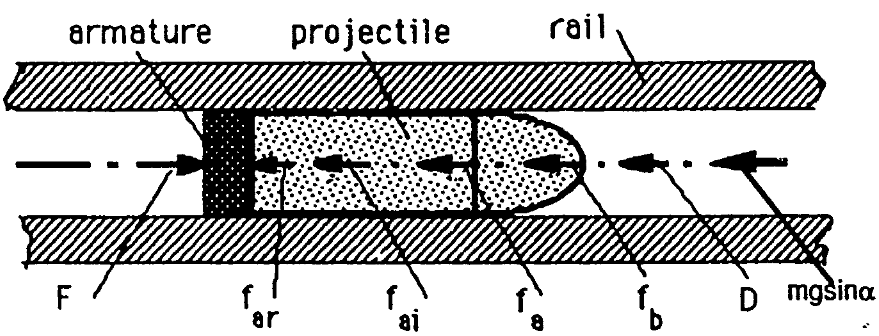

Figure 1. Barrel and projectile package configuration and axial forces

The governing equation is formulated from Newton's second law of motion as follows

$$ma = F - f_{ar} - f_{ai} - f_a - f_b - D - mg\sin\alpha \quad (1)$$

where

- m = mass of projectile package or sum of masses of armature and projectile
- a = axial or x-direction acceleration of projectile package
- F = total propulsion or Lorentz force
- f_{ar} = resultant friction force between armature and rail due to uniform circumferential compression
- f_{ai} = resultant friction force between armature and insulator due to uniform circumferential compression
- f_a = friction force between armature and rail due to projectile package weight
- f_b = friction force between bourrelet and rail due to projectile package weight
- D = drag force of air resistance
- g = gravitational constant = 9.81 m/sec/sec
- α = inclination of x-axis or barrel with respect to the horizon (angle of elevation)

Friction forces (f_{ar}, f_{ai}, f_a and f_b) will be determined from the friction coefficients and the design or actual contact pressure at the armature-rail, armature-insulation, bourrelet-rail and bourrelet-insulation interfaces. They are difficult to determine and some simplified approximations from experiments are recommended. The friction equations are derived from geometrical conditions, force reactions, and the friction law as follows:

$$f_{ar} = 2\mu_{ar} R b p_r \beta \tag{2a}$$

$$f_{ai} = 2\mu_{ai} R b p_i (\pi - \beta) \tag{2b}$$

$$f_a = \mu_{ar} \frac{h}{\ell + h} mg\cos\alpha \tag{2c}$$

$$f_b = \mu_b \frac{\ell}{\ell + h} mg\cos\alpha \tag{2d}$$

where

- μ_{ar} = friction coefficient of armature on rail
- μ_{ai} = friction coefficient of armature on insulation
- μ_b = friction coefficient of bourrelet on rail
- b = width of armature circumferential contact
- p_r = contact pressure between armature and rail
- p_i = contact pressure between armature and insulation

R = radius of barrel bore
β = angle subtended by rail with respect to barrel center
π = 3.141593
ℓ = distance between center of gravity and base of armature
h = distance between bourrelet and center of gravity

However, these frictions may be ignored if the coefficients of frictions are low, which are the usual cases.

The drag force of air resistance, D, may be computed from the aerodynamic drag equation

$$D = .5\rho AC_D v^2 \qquad (3)$$

where

ρ = air density
A = bore cross-sectional area
= πR^2
C_D = drag coefficient
v = axial velocity of projectile

The Lorentz force, F, may be computed from a special formula using rail current and inductance values

$$F = .5L'I^2 \qquad (4)$$

where

L' = rail inductance per unit length
I = rail current

However, more complicated Lorentz force formulations may be used when they are available.

Substituting the friction and air resistance equations (2 and 3) into equation 1, the equation becomes

$$a = [F - 2\mu_{ar} Rbp_r \beta - 2\mu_{ai} Rbp_i (\pi - \beta) - \mu_{ar} \frac{h}{\ell + h} mg\cos\alpha$$

$$- \mu_b \frac{\ell}{\ell + h} mg\cos\alpha - .5\rho AC_D v^2 - mg\sin\alpha]/m \qquad (5)$$

If the α angle is small, then equation 5 may be further reduced to the following form:

$$a = [F - 2\mu_{ar}Rbp_r\beta - 2\mu_{ai}Rbp_i(\pi - \beta) - (\mu_{ar}h + \mu_b\ell)\frac{mg}{\ell + h} - .5\rho AC_D v^2]/m \qquad (6)$$

To get the upper bound of the acceleration, the friction forces, weight of projectile, and air resistance may be also ignored. Consequently, equation 6 becomes

$$a = F/m \qquad (7)$$

Many engineers and scientists use this formula although the computed result is usually 20 to 40 percent larger than obtained from experimental data. Sometimes an empirical correction factor, C, is used which represents the effect (in proportion to the Lorentz force) of the sum of the frictions, air resistance, and gravity forces on the right-hand side of equation 5. This reduces the magnitude of the propulsion force in order to make the computation more nearly agree with experimental results. The value of C ranges approximately 0.2 to 0.4. Using the correction factor, C, the equation becomes

$$a = F(1 - C)/m \qquad (8)$$

The axial or x-direction velocity, v, and the travel or displacement ,x, of the projectile are the first and second integration of acceleration with respect to time, respectively. They are

$$v = \int_0^{t_1} a\,dt \qquad (9)$$

$$x = \int_0^{t_1} v\,dt \qquad (10)$$

Solution of Governing Equations

The procedure to solve the governing equations is as follows:

Acceleration is computed first. Velocity and displacement then may be solved in a closed form if it is easy to perform the first and second integrations of the acceleration with respect to time. Otherwise, standard numerical integration techniques may be used to compute them.

When the acceleration is constant, a closed form solution is obtained by integration. The velocity and displacement at any time, t, are

$$v = at \qquad (11)$$

$$x = .5at^2 \quad (12)$$

and consequently,

$$t = v/a \quad (13)$$

$$v = \sqrt{2ax} \quad (14)$$

$$x = \frac{v^2}{2a} \quad (15)$$

Sample of Computation

A simple example with no frictions or air resistance is presented below. It shows the computation of the case where the input current versus time curve is shown in figure 2. The other data of input are

Barrel length = 4 m
Mass of armature, m_a = 0.002 kg
Mass of projectile, m_p = 0.003 kg
Rail inductance gradient, L' = 0.35 μH/m

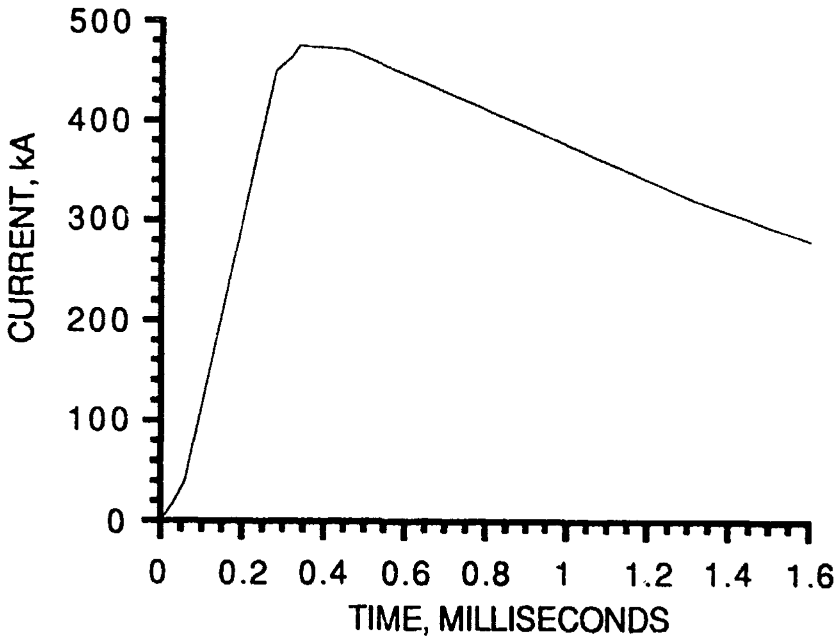

Figure 2. Rail current versus time

Using the numerical integration procedure, the acceleration, velocity and displacement are computed and the results are plotted in figures 3 through 7.

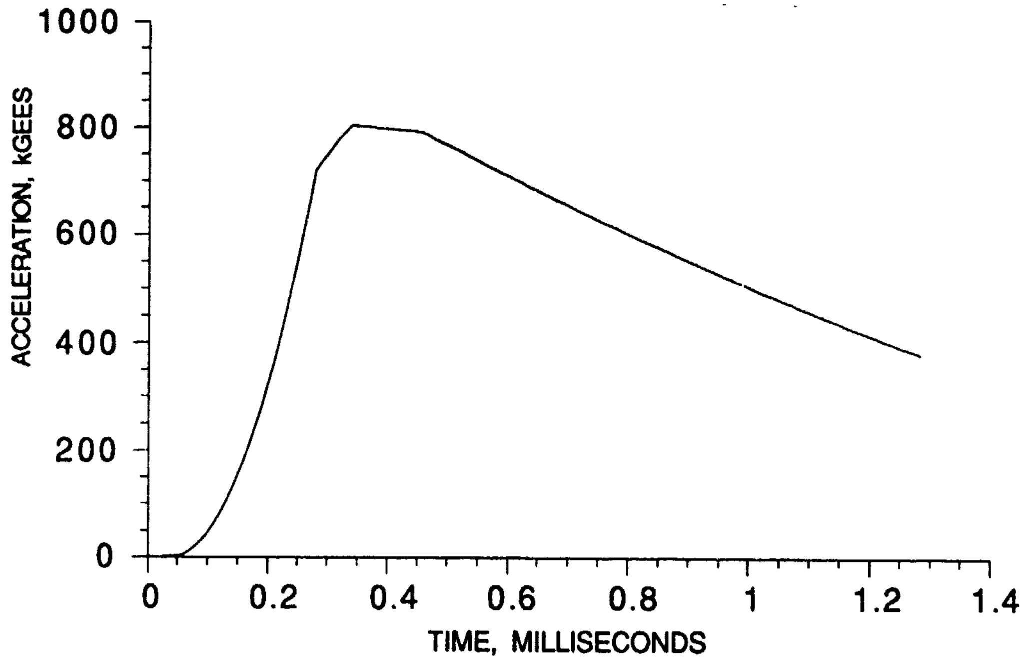

Figure 3. Acceleration versus time

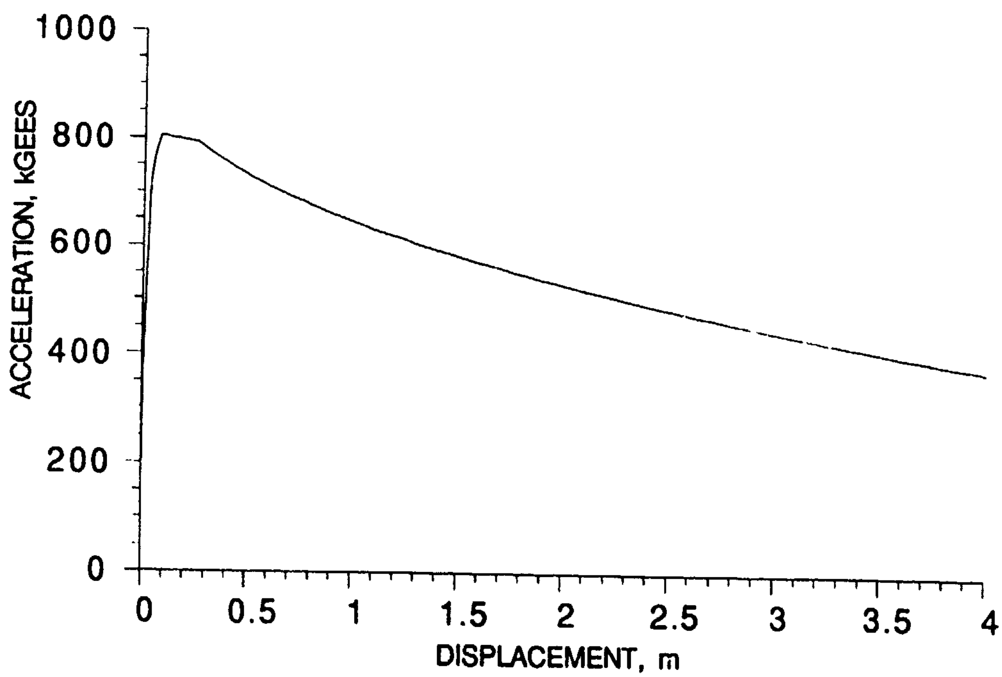

Figure 4. Acceleration versus displacement

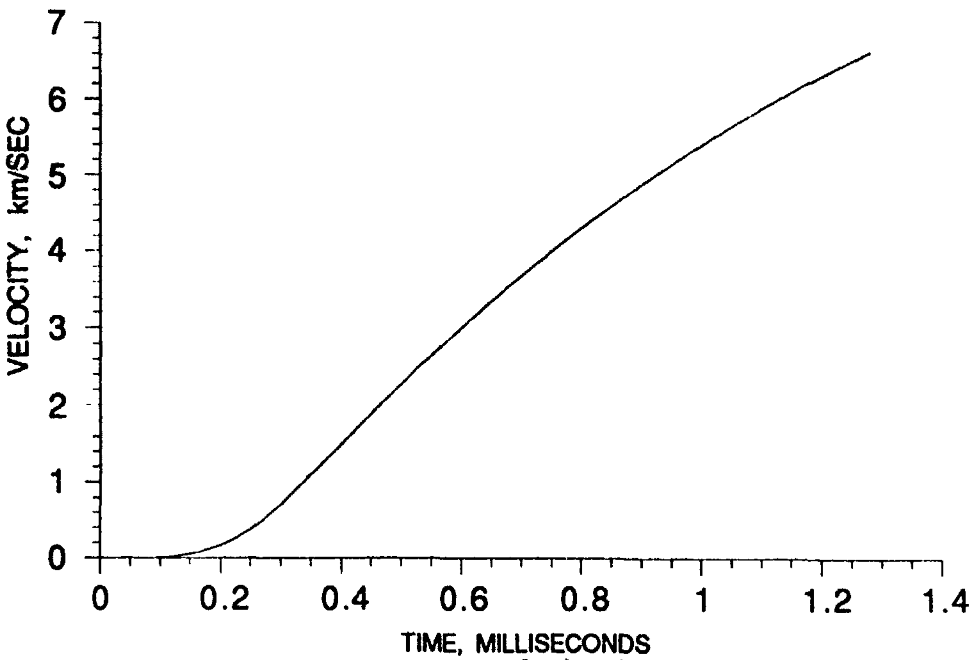

Figure 5. Velocity versus time

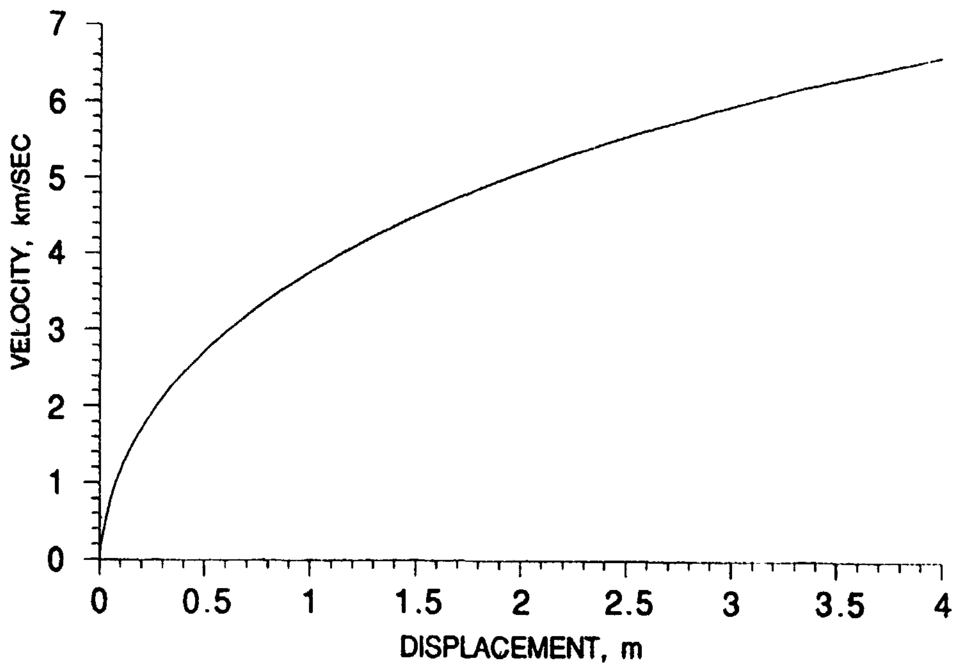

Figure 6. Velocity versus displacement

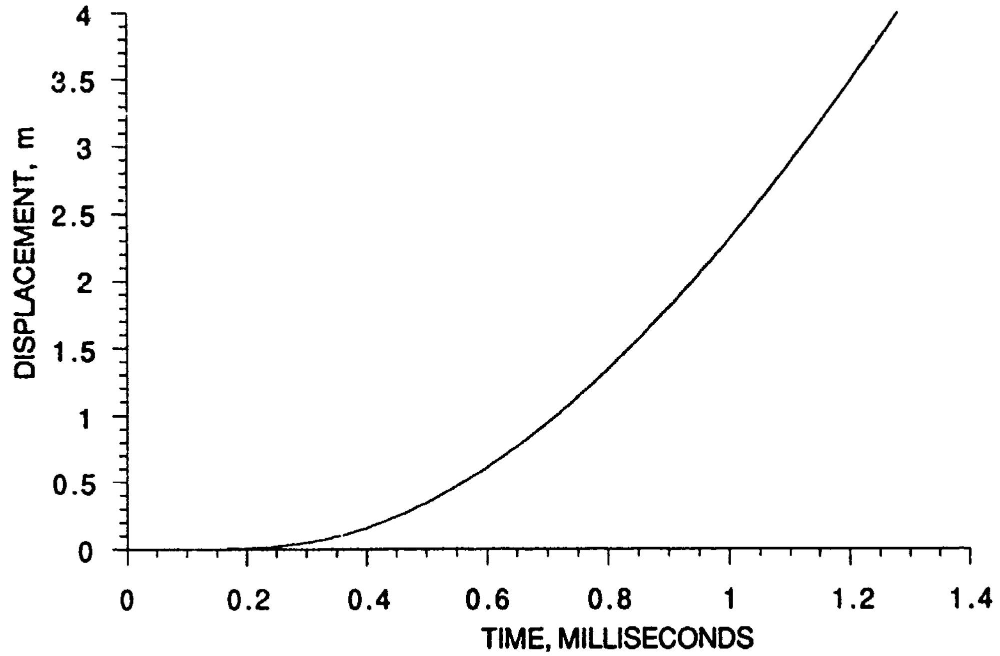

Figure 7. Displacement versus time

When the rail current is constant, say 475 kA, the acceleration is also a constant. Using equation 4, the propulsion force is

$$F = .5L'I^2 = 39.5 \text{ kN} \quad (16)$$

Substituting this value and the mass data into equation 7, the acceleration of the projectile package, a, is computed as

$$a = F/m = 805 \text{ kgees} \quad (17)$$

Then, the velocity, v, when the projectile package is at the muzzle, is computed using equation 14, and the value is

$$v = \sqrt{2ax} = 8 \text{ km/sec} \quad (18)$$

The corresponding time is

$$t = v/a = 1 \text{ ms} \quad (19)$$

CONCLUSIONS

Utilizing Newton's second law of motion and making a number of logical assumptions on the various forces occurring within the electromagnetic railgun, a set of simple basic equations has been derived. With these equations it is possible, when the current versus time profile is known, to calculate approximate values for the acceleration and velocity of the projectile package as it moves along the railgun and the associated values for time and travel (displacement). Plotting these calculated acceleration and velocity values versus time or travel provides a good approximation of the axial motion of the projectile package.

Further experimental data is necessary to enhance the accuracy of the assumptions, e.g., the magnitude of the frictional forces within the railgun.

More complicated models will be introduced in subsequent reports which will include lateral forces and gun tube vibration effects.

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Chu, Szu Hsiung, "A Simple Theoretical Model for Projectile In-Bore Motion of Electromagnetic Railguns," pp. 204-223, Proceedings of the Fifth U.S. Army Symposium on Gun Dynamics, Special Publication ARCCB-SP-87023, U.S. Army ARDEC, Benet Laboratory, Watervliet, New York, September 1987.

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