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COMPARISON OF ELECTROMAGNETIC AND CONVENTIONAL GUNS FROM A MECHANICS AND MATERIAL ASPECT

Jerome T. Tzeng and Edward M. Schmidt

Weapons and Materials Research Directorate
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ABSTRACT

Electromagnetic (EM) railguns are similar to conventional guns in that both provide an accelerative force to the projectile while containing the loads on the bore. Each is subjected to extreme thermal and erosive environments. However, there are also fundamental differences due to the propulsion mechanisms. The present paper compares these two types of launchers with emphasis on structural and material aspects.

INTRODUCTION

For many years, the utility of electric weapons has been explored. Recently, progress in pulsed power, launcher, and projectile technology has broadened interest in the electromagnetic gun. Unlike particle beams or high-power microwaves, the EM gun provides hypervelocity launch for relatively massive bodies. For application to ground combat, the EM gun system must be compatible with mobile platforms and emphasis is placed on robust, compact, low-mass components capable of sustained operations in a field environment. This paper addresses design, mechanics, and materials of a particular type of EM launcher, the railgun, and makes broad comparison to the main features of conventional powder guns.

The schematic in Figure (1) illustrates the essential components of a railgun, including the rails, projectile, and loading conditions. Current flows from the breech through one rail, across the armature (an integrated part of the projectile package), and then returns through the other rail. When current flows in the circuit, a magnetic field is established in the space between the rails. This field interacts with the current to produce the Lorentz or **J**x**B** force, which accelerates the projectile and produces a mutually repulsive force on the rails. The electromagnetic forces (body forces) in railguns are not axisymmetric like in conventional, propellant-based guns. Instead, the

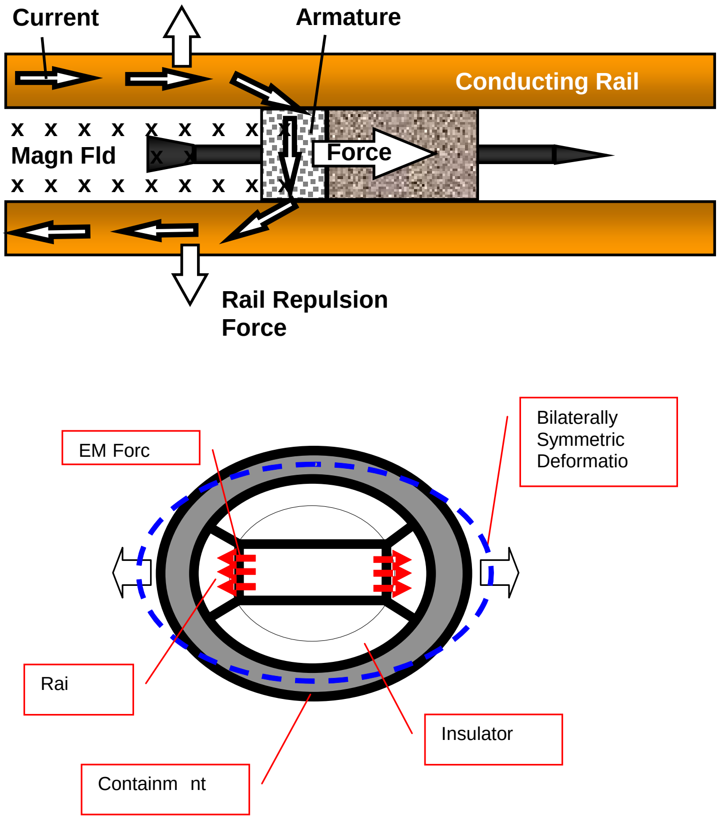

Figure 1. Schematic of EM railgun and gun bore.

forces concentrate only on the rails through which it is transferred to the containment/support structure.

The rails have to be electrically separated by insulator materials and confined by a robust containment structure. Accordingly, a railgun is not constructed from a single material with simple geometry. The design of each individual railgun component and their interfaces is not obvious. In fact, it is a significant challenge to optimize the gun bore configuration and material selection if weight constraints, reliability, and performance are considered for a tactical weapon.

This paper will compare conventional and railguns from a mechanics and material aspect. Since railguns use advanced composite materials, consideration will be given to both a steel and composite conventional gun. This will serve to provide a better relative comparison of technologies.

NOMENCLATURE

B = magnetic flux density
I_ρ = linear current density
J = current density per area
L' = inductance gradient of railgun
m_c = mass of cartridge
m_p = mass of propellant
p_{base} = pressure at the base
p_{breech} = pressure at the breech

LAUNCHER SYSTEMS CONSIDERED

A comparison is made between two classes of medium caliber cannons: the Mauser 30-mm MK 30-2 and a notional EM launcher [1]. Both fire long rod, kinetic energy projectiles, Figure 2, at equivalent muzzle energies and with penetration capabilities. The Mauser fires an Oerlikon PMC287 kinetic energy projectile at a velocity of 1405 m/s. The EM railgun also fires a KE penetrator at a postulated velocity of 2300 m/s. The EM gun is a simple railgun with a 14.5- × 32.7-mm rectangular bore. It is powered by a multiphase pulsed alternator [2]. Relatively high values of inductance gradient [6], $L' = 0.55\ \mu\text{H/m}$, and linear current density [7], $I_\rho = 47.7$ kA/mm, are assumed resulting in a launcher with 3.35 m travel. The basic characteristics of the two launcher systems are given in Table 1.

Table 1. Comparison of launcher systems.

	Mauser 30	**EM**
Projectile		
V_m (m/s)	1405	2300
a_{max} (kG)	84	149
m (kg)	0.235	0.090
E_m (MJ)	0.232	0.238
Launcher		
D_{bore} (mm)	30	14.5 x 32.7
L (m)	3.41	3.35

30mm, Oerlikon, APFSDS T, PMC287, V = 1405 m/s

EM Hypervelocity Round, V = 2300 m/s

Figure 2. Projectiles under consideration.

For equal muzzle energies, the length and bore dimensions are comparable; however, since there is a significant difference in muzzle velocity for roughly the same gun length, the in-bore acceleration of the EM projectile is obviously greater. This level of acceleration has been successfully demonstrated with other medium-caliber EM projectiles [3].

From a gun design standpoint, the in-bore pressure histories are of more concern. After hundreds of years of evolving, the conventional gun is well optimized in terms of mechanics and materials. The gas pressure distribution is basically axially symmetric. The chamber gas pressure and the projectile base pressure of Mauser-30mm are presented in Figure 3. The tube walls experience the full projectile base pressure and must be designed to sustain it.

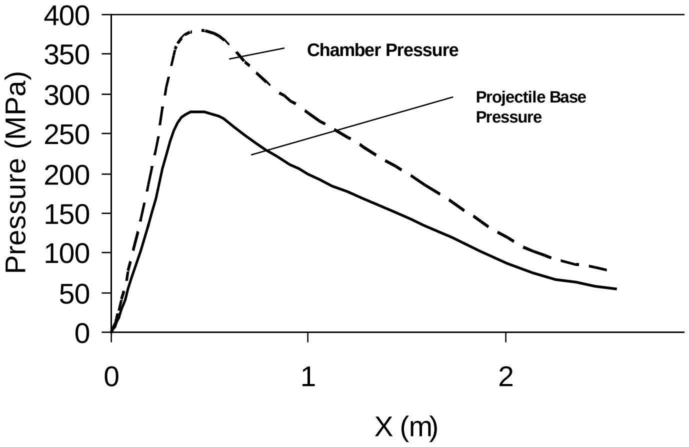

Figure 3. In-bore pressure distribution, 30-mm Mauser.

In contrast with an EM gun, the projectile base pressure and the rail pressure differ mainly due to the fact that the projectile experiences the magnetic field generated by both rails whereas the rails only experience the field of their opposite. For a simple railgun, the rail pressure is one-half the value on the projectile base. Based on the current profile by Kitzmiller, et al, [2], the projectile base and rail pressures can be estimated and shown in Figure 4. Comparing conventional and EM pressures, it is not surprising that the base pressure levels are of a similar magnitude since the muzzle energies and tube lengths are roughly equivalent; however, the rail pressure level of the EM gun is significantly lower than the gas pressure with the powder gun.

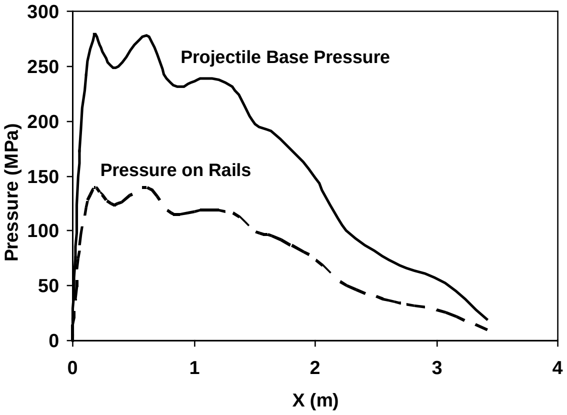

Figure 4. Pressure distributions, hypervelocity railgun.

Mauser 30-mm MK 30-2

Two cases are examined: the existing steel barrel and a notional composite barrel. The latter is intended to place the comparison between the conventional and railguns on a similar technical basis. The ballistic performance is taken to be identical in both cases.

The inner and outer radius near the forcing cone region is 15 and 38 mm, respectively, while the thickness of the steel wall is 23 mm. If the maximum chamber pressure is 380 MPa, the circumferential stress will be 520 MPa and 140 MPa at the inner and outer radii, respectively. The yield stress of the 4340 gun steel is 1050 MPa; thus, providing a safety margin around 2. The mass of the MK 30-2 is given as 80 kg.

For the notional composite Mauser, the material selected is metal matrix composite. The bore has the same geometry as the 30-mm steel gun. The moduli of the composite in the circumferential and radial directions are 240 and 160 GPa, respectively. It is an all-hoop wound tube with fiber oriented along the circumferential direction. The circumferential stress at the innermost radius is calculated to be 470 MPa and 110 MPa at the outermost radius. The stress profile through the thickness is strongly affected by the anisotropy of hoop and radial stiffness of composite construction. Table 2 lists a comparison of the calculated stresses and properties of the steel and composite tubes. The weight of composite gun is estimated to be 35 kg, compared to 60 kg for the steel barrel.

Table 2. Properties of steel and composite 30-mm Mausers and EM gun.

	Steel 30	**Composite 30**	**EM**
Chamber Press (MPa)	380	380	140
Circum. Modulus (GPa)	210	240	Varies
Radial Modulus (GPa)	210	160	Varies
Innermost Hoop Stress (MPa)	520	470	450
Outermost Hoop Stress (MPa)	140	110	700
Mass of Tube (kg) (Estimated)	60	35	50

EM Railgun

Unlike a conventional gun, the electromagnetic force (body force) in a railgun is not axisymmetric but concentrates on the rails and nearby conducting structures leading to a bilaterally symmetric deformation and stress state. Generally, the current in the rails and associated magnetic field extend from the breech to the armature location. There is little spatial variation in the repulsion force along the axis of the railgun at any given time. However, temporal changes do occur as the current provided by the pulsed power system varies during the in-bore cycle. This results in transient structural response in the rails, insulator, and containment as the projectile moves along the gun tube at an extremely high velocity. Dynamic response of rail due to projectile/rail interaction has been recently investigated [4]. Since railguns are not constructed from a single material with a simple geometry, selecting optimal material to balance electrical and mechanical performance is a significant challenge.

The EM railgun has a generic geometry, Figure 1. The railgun has a 14.5- x 32.7-mm rectangular bore with copper rails, ceramic insulators, and a composite structural overwrap. The material and moduli are as follows: rail = 126 GPa (copper); containment = 140 GPa (carbon composite); and insulation = 280 GPa (ceramic). Due to complexity of geometry and loading condition, finite-element analysis is needed. The displacement fields in the horizontal and vertical directions, respectively, are given in Figures 6 and 7. The concentration of the EM load on the rails results in an elliptical-shaped deformation of the barrel. The rails move outward while the insulators are forced inward by the reaction of the containment. This produces significant loads on the insulator materials. The deformation can cause bending and shear in the containment structure. The magnitudes of deflection and stresses are determined by the aspect ratio of the elliptical-shaped gun bore and the stiffness of each component. A railgun must be designed to properly achieve a balanced stress profile in the insulators, rails, and composite containment.

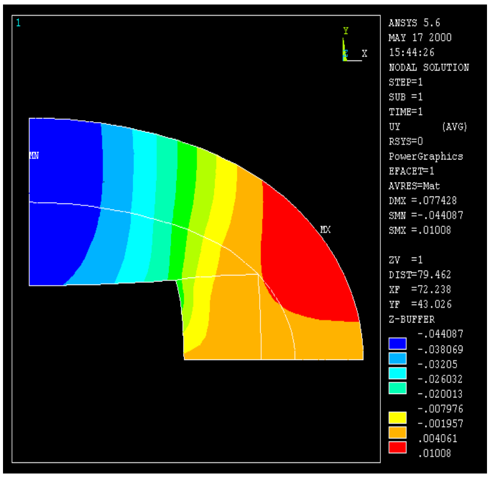

Figure 6. Horizontal displacement profile.

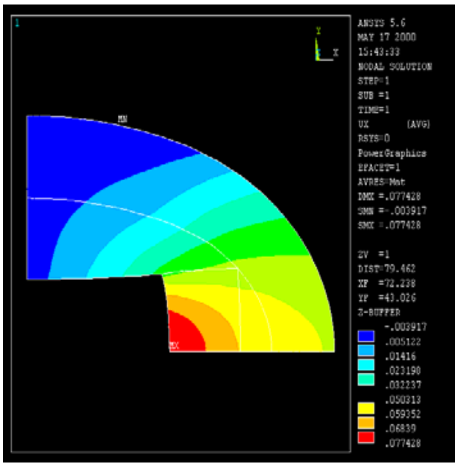

Figure 7. Vertical displacement profile.

The estimated stresses and barrel mass are listed in Table 2. The hoop stress in the composite can be estimated from the radial deformation in the region near the insulator. The fiber stress mainly results from the extension of the composite as the rail moves radially outward and is calculated to be between 450 and 700 MPa. The mass of barrel, estimated from the generic barrel geometry, is around 50 kg.

Materials for rails, insulators and containment are quite different since each serves its particular function. The stress analysis from the previous section provides an understanding of the mechanical and material requirements for a viable railgun design. Based on this analysis, material requirements and choices for each component are considered. Rails are probably the most heavily loaded components in a railgun. The rails will need stiffness and strength to resist the EM force and must provide good electrical conductivity while sustaining joule heating, especially at the armature contact location. Copper and aluminum alloy conductors are commonly used; however, there is no single material that can satisfy all requirements as a rail. An alternative solution is to combine a hard cladding layer for the rail surface and high conductive material for the rail body. For railguns, it must be remembered that current flows through the cladding and generates heat which can stress and separate the interface.

In addition to providing an electrical barrier insulator material serves a critical structural function to carrying and transferring the EM loads in the gun bore. Ceramic and G10 composite (fiber glass composite) are used in EM launchers. The major shortcoming for ceramic is its relatively low tensile strength. G10, an anisotropic material, is a common insulator material used in the railguns because it can be machined easily and is widely available. However, thermal stability and surface wear are the shortcomings.

Ideally, the containment should provide stiffness and strength to maintain dimensional stability in the gun bore, transfer the EM force from the rails and insulators, and provide a preload mechanism to maintain the gun bore intact. A fiber-reinforced composite overwrap is suitable if the bore expansion (rail separation) can be sufficiently contained. Carbon composite can be effectively used as containment because it is stiff, strong, and lightweight. The laminate architecture can be designed for the requirement of stiffness and strength in the hoop and axial directions of the gun barrel.

CONCLUSIONS

The difference in propulsion force, thermal load, and launch mechanism make the comparison of the EM and conventional guns interesting but not straightforward. Examples are presented that compare the mechanics and materials of an electromagnetic railgun with that of a similar caliber and performance conventional cannon. Both must be capable of efficiently managing the propulsive force; however, the force distribution in the railgun and the material requirements for electric propulsion result in quite different design consideration. A combined mechanics and material approach is needed to integrate various components such as the rails, insulators, and containment for an efficient EM launcher.

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