Structural Mechanics for Electromagnetic Rail Guns

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Abstract - The objective of this investigation is to explore potential designs and appropriate materials for a lightweight fieldable electromagnetic rail gun. Lessons learned from the previous launcher designs are reviewed and discussed from a mechanics point of view. Analyses are performed with a conceptually workable gun bore to illustrate the requirement of a fieldable gun construction. Both static and dynamic responses of the rail gun are discussed. The study provides a fundamental understanding for developing a fieldable rail gun in terms of mechanics and material requirement.

Introduction

Many electromagnetic (EM) rail launchers have been built in the past two decades in university, industry, and government labs. As laboratory guns, these launchers were designed mainly from an electrical performance point of view. There are advantages and shortcomings for those designs and configurations. A critical review of those configurations was conducted from material and mechanics aspects. Three EM rail gun designs built in the past are illustrated in Figures 1,2 and 3. A laminated steel barrel [1] developed by International Applied Physics (IAP) is shown in Figure 1. Many of the laminated barrels are used in the laboratories because of good electric efficiency and easy assembly (e.g., replacing rails, insulator, etc.). The laminated steel construction provides excellent circumferential stiffness and confinement for the rails and insulator. However, it lacks strength in the longitudinal direction and is too heavy for a fieldable weapon application.

A 90 mm 9 MJ range gun [2] was developed at Center of Electromagnetic (CEM) of the University of Texas as shown in Figure 2. This is basically a laminated steel gun wrapped with a polymer composite shell. This gun design is similar to the laminated steel rail gun and uses the laminated steel containment and the composite shell to provide the circumferential confinement. The shortcomings of this design are similar to the laminated steel guns, again lacking longitudinal strength. Potential failure might occur at the laminate interface of steel containment. There is also a potential shortcoming of weight. The Cannon-Caliber Electromagnetic Gun (CCEMG) [3] is shown in Figure 3. A flatjack is used as a prestress mechanism that keeps the rails and gun bore intact during the launch of a projectile. Concerns for this type of design include the possible loss of preload over a period of time and the feasibility of using it in a tactical system.

The rail launchers developed so far have a relatively short service life when compared to a conventional cannon because of rail and insulator failure. These failures might result from the lack of material strength and structural integrity of design. In many gun designs, a high prestress is employed in order to keep the rail and insulation materials intact during launch of a projectile. However, there are concerns with using the preload mechanism. The preload might decrease over a period of time if the insulator material such as G10 (glass composite) creeps and causes the change of prestress. The reduction of preload could affect the performance of the rail gun. From the aspect of structural design, the prestress could weaken the rails and insulation materials by "consuming" the strength of material. A complete understanding of each particular design will be needed to determine this effect. Generally, it is true that prestress built in the rail and insulator could indeed weaken these components. It can be concluded from reviewing the many rail gun designs that a combined mechanics and material approach might shed light on building a fieldable and longer service life gun.

Unlike a conventional gun, the EM load is not as axisymmetric as a chemical gun but concentrates more on the rails and part of the containment or support structure. The load is complex such that electromagnetic force and possible plasma pressure can vary in time and space along the rail gun during launch. The load is also highly transient in nature due to the hypervelocity launch. As illustrated in most designs, a rail gun cannot possibly be constructed from a single material with simple geometry because of electrical and mechanical requirements. It is a significant challenge to design each individual component and the interfaces between the components of a rail gun, particularly to achieve an optimal material selection and a balanced electrical and mechanical performance. A finite element analysis of a viable railgun bore is performed in this

study to provide an understanding of mechanical loads and material requirements for a rail gun section design. An evaluation on the basis of the analysis can then provide some understanding for design and fabrication of a rail gun from the mechanics and material points of view. This study performs a generic structural and material evaluation for a conceptual rail gun and makes recommendations based on the results

Structural Modeling

Although the geometry and structural design are drastically different, there are some similarities between various configurations and designs. The loading conditions in the rail are basically the same in terms of how they are applied. They are nonaxisymmetric, concentrated in the rails, and are transient because of the movement of the projectile. Figure 4 shows a schematic of the gun bore configuration and loading conditions in a rail gun. The rails are compressed against the outer containment structure as a result of the EM force. The magnetic load on the rail is presumably discontinuous at the front location of armature/rail interface. The discontinuity of the force causes local bending and shear stresses in the rails near the armature location. These stresses move along the rails as the projectile moves down through the barrel. As shown in Figure 4, a nonaxisymmetric EM load results in an elliptical-shaped deformation of the barrel. Accordingly, there are "reactive" forces acting on the insulation material. This force could result in bending and shear in the insulation along the barrel length.

A simple elastic analysis is performed to illustrate the mechanical response of a barrel under EM forces [4,5]. The material properties of components are based on the choice described in the previous section. Figure 5 shows a generic gun bore which can represent any type of specific rail gun design. A pressure load of 110 MPa is applied on the inner surface of the rails to represent the EM forces. The moduli of each component (assumed here to be isotropic) are as follows:

Rail:	18 Msi	(Copper)
Containment: composite)	20 Msi	(Carbon
Insulation:	40 Msi	(Ceramic)

Figure 6 shows the deformation of the bore under the 110 MPa pressure load. The magnetic pressure is applied on the inner surface of the rails. The shape of deformation is as expected and is described in Figure 4. The upper part (a quarter symmetry finite element model) of the bore moves inward as the rail moves outward. The displacement in the X and Y directions are shown in Figures 7 and 8, respectively. The largest X displacement is about 0.077 mm (0.003 inch) in the rail, which is believed to be within the acceptable range. The Y displacement is also small and within a workable range. These results indicate that the stiffness of the bore is sufficient to avoid in excessive deformation.

The stress components in the X direction are shown in Figure 9. The stress in the rail is 110 MPa at the rail surface, which is the boundary condition. There is concern about the tensile stress of 250 MPa (36 ksi), at the lower part of the insulation. It is critical but probably within the acceptable range, since the tensile strength is around 345 MPa (50 ksi) for a common high strength ceramic. The stress is approaching the material limit if the uncertainty of ceramic properties is considered from a static point of view. However, this tensile stress can be reduced through a change in the aspect ratio of the bore or using a stiffer containment construction. The Y stress component for the structure is shown in Figure 10. It is small and, in general, not critical. It is noted this analysis doesn't consider the stress caused by vibration or dead weight, particularly in the direction along the gun length.

It is interesting and worthwhile to comparing the stress and deformation in an EM rail gun and a conventional barrel, even for a generic geometry. The cross section and propellant pressure of a conventional cannon are both axisymmetric. The major stress in the gun is a membrane force. Accordingly, there is no bending moment developed in the cross section. As previously established, an efficient structure can be obtained through introduction of an autofrettage process. On the other hand, the EM loading is distributed in the rail cross-section and thus requires a careful and intelligent structural and material design. The longer but lower magnitude acceleration pulse of the EM launchers results in a lower force level in the gun bore. This is a great advantage for EM gun design to be compatible with conventional cannons in terms of performance. As discussed, very high prestress is applied to keep the barrel intact in several previous barrel designs. Since the EM force causes compression in the rails, the preload can actually weaken the rails and insulators. A good barrel design might be achieved to prevent the weakening effects of the preload on the insulation as well as rail materials.

Gun Dynamics

The dynamic response of the barrel might be a concern for the EM launchers just as for conventional guns. Very large strains have been observed in the conventional tank guns due to resonance occurring in the barrel. Dynamic response of the barrel becomes critical for increased projectile velocity and lightweight barrel designs [6-8]. A fieldable EM barrel requires being both lightweight and able to launch projectiles at hypervelocity. Accordingly, dynamic analysis should be considered in the barrel design.

Consider a railgun cross section, as shown in Figure 4. The rail has a rectangular cross section and is mechanically supported by a rigid material, a containment structure, and insulation material. The structural response of the rail can be modeled as a beam sitting on an elastic foundation, as shown in Figure 11. Accordingly, the rail is the beam, and the support from the insulation material and containment is modeled as an elastic foundation [9,10]. It is assumed that structural interaction between the rail and the containment is modeled through the elastic constant. The magnetic pressure traveling at the speed of the projectile on the rail can be expressed as a Heaviside step function. The governing equation for the rail gun subjected to a moving pressure can then be derived as follows:

$$m\frac{\partial^2 w}{\partial t^2} + EI\frac{\partial^4 w}{\partial x^4} + kw = q[1 - H(x - Vt)].$$

(1)

Here, w is the lateral displacement dependent upon time, t, and axial position coordinate, x; The symbol, m, is the mass per unit length and is equal to ρBh; ρ is the density of rail material; and B and h are the width and thickness of the rail, respectively; E is the modulus of rail material and I is the moment of inertia of the rail cross section. The elastic constant, k, from the elastic foundation will be derived from either a closed form or numerical solution such as finite element analysis. The loading function, q(1 - H(x-Vt)) in Equation (1), represents the magnetic pressure front traveling along the rail with a constant velocity, V, represented by a Heaviside step function, H(x-Vt). The magnetic pressure, q, is assumed to be constant also. Accordingly,

$$q(1 - H(x - Vt) = 0 \qquad when \ x > Vt$$
$$= q \qquad when \ x \le Vt$$

(2)

Equation (1) can be solved using separation of variables with the assumption of

$$w(x,t) = \phi(t)\theta(x).$$

(3)

where $\phi(t)$ and $\theta(x)$ represent the time and position variables of $w(t,x)$, respectively. Accordingly, the left-hand side of Equation (1) can be rewritten to solve the homogeneous solution as follows:

$$m\ddot{\phi}\theta + EI\phi\theta'''' + k\phi\theta = 0.$$

(4)

Equation (4) can be solved using Lagrange approach with specific boundary conditions such as cantilever gun support. A separate report will be compiled to detail the solution. For the interest of understanding the dynamic characteristics of a rail gun, the critical velocity is one of the most important indexes to illustrate the integrity of a rail gun. The critical velocity of the beam (rail) can be derived from the characteristic function and the particular solution from Equation (3) as follows:

$$V_{cr}^2 = \frac{1}{\sqrt{3}}\frac{1}{\rho}\sqrt{\frac{h}{B}}\sqrt{E}\sqrt{k}.$$

(5)

Equation (5) shows that the critical velocity of a rail gun subjected to a moving pressure front is a function of the rail geometry, density, and elastic modulus. In addition, the support from the containment structure has great influence on the dynamic behavior of the rail. Critical velocity increases with the elastic modulus of the rails and the stiffness of containment structures. From a design point of view, a launcher that is constructed with high stiffness and lightweight material with a large moment of inertia is preferred for dynamic loading conditions.

A test case is used for a critical velocity parametric study can be obtained using a test case from [10]. The gun is composed of a pair of metal rails and a circular steel containment. Table 1 illustrates a set of properties and geometry for a test case. Although these parameters do not represent any specific design, the simulation can be used to illustrate why the critical velocity might be critical for a rail gun design.

The elastic response from the containment can be calculated from Castigliano's theorem from the reference [10] as the input to the Equation (5). Accordingly, the critical velocity of the barrel can then be calculated as follows:

$$V_{cr} = 1148 \ m/sec.$$

(6)

From an application point of view, the calculated critical velocity can be an indication if the design is appropriate for further development. It is obvious the number as shown cannot be accepted for high performance tank gun application. However, it is noted that the simulation above does not apply to any specific gun design. It is a pure exercise of model simulation.

In general, the critical velocity is strongly dependent on the cross section geometry and the mechanical properties of rail and containment. It is an indication of the structural stiffness and integrity of gun bore under dynamic loading conditions. The model is based on the assumption of no structural coupling effects from insulation materials. It is a reasonable assumption for a lower bound solution since the bonding between rail and insulation is assumed as friction only. A low critical velocity in general suggests that the gun dynamics shall be

129

considered in more elaborated fashion for a rail gun design.

Conclusions

A preliminary analysis has been performed with a conceptually workable barrel design to illustrate the mechanical response of an EM barrel under static and dynamic loads. Accordingly, the analysis was further discussed from a material aspect to illustrate the requirement for an EM barrel construction A three-dimensional analysis with anisotropic material properties will be required to evaluate the bending and shear along the axial direction of the gun. The preload mechanism to keep the gun bore intact in many previous designs might need to be reevaluated and an innovative design might be able to provide a similar mechanism without the prestress. Laminate architecture of various composite components could be designed to achieve balanced properties in all directions. Finally, the dynamic response of the gun barrel might need to be further examined for a fieldable system since hypervelocity is an artifact of the rail gun performance.

References

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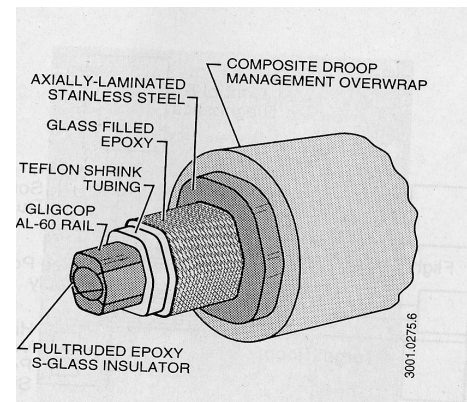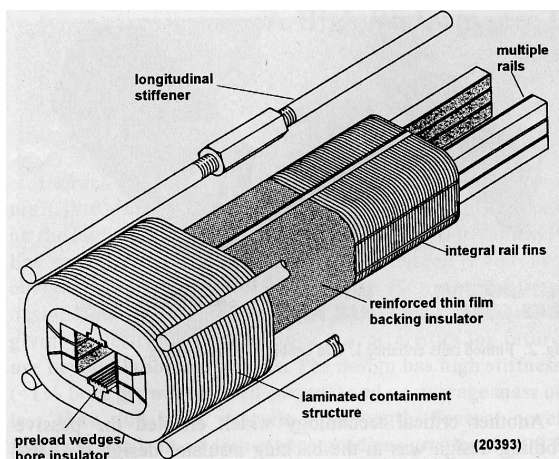
Figure 2. 9MJ range gun [2].
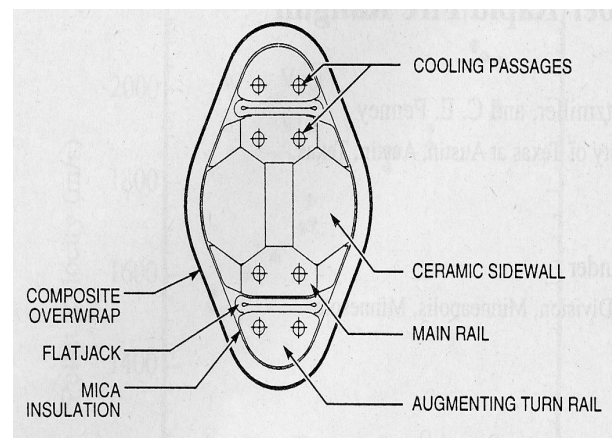

Figure 1. Most steel laminated rail gun [1].

Figure 3. Cannon-caliber rail gun [3].
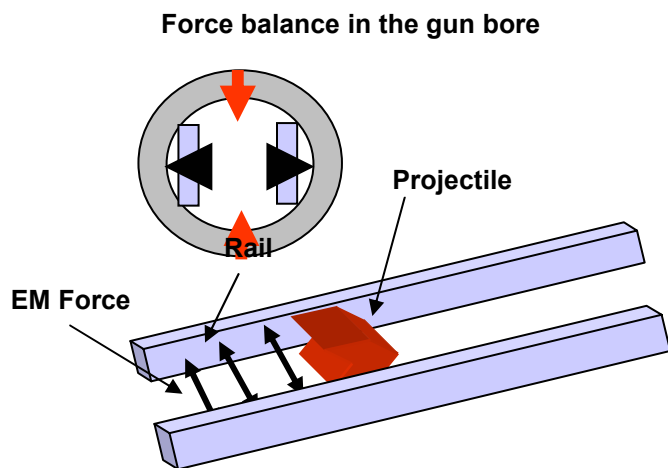
Force balance in the gun bore

Figure 4. A conceptual gun configuration.
The loading condition is generally similar
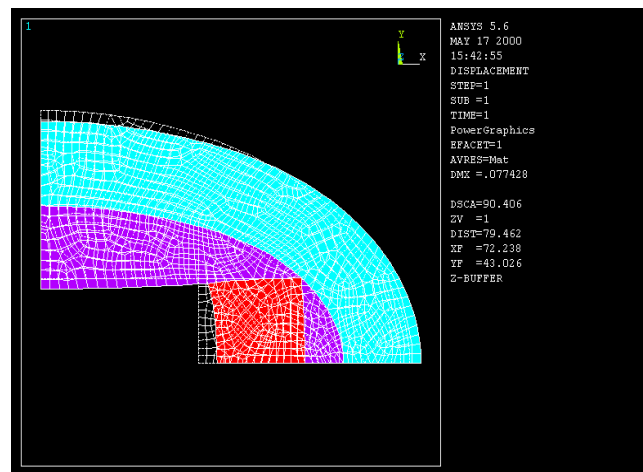for various rail gun design.

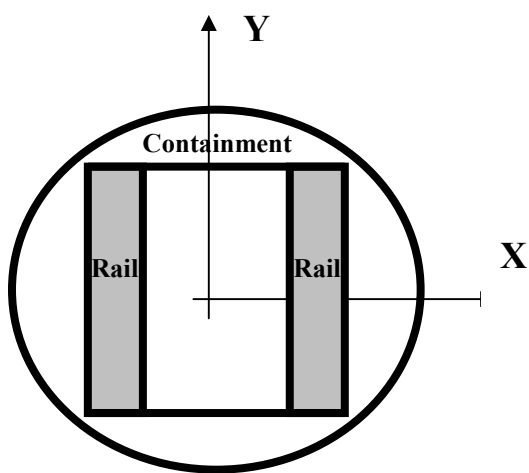Figure 6. Deformation of Barrel section

Figure 5. A conceptual rail gun geometry
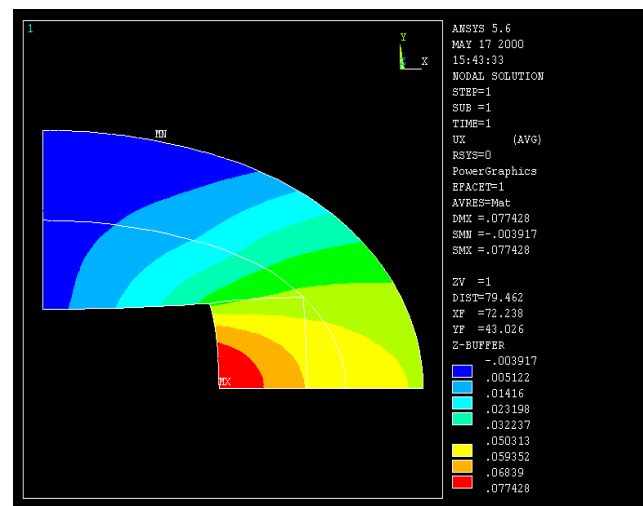for simulation.
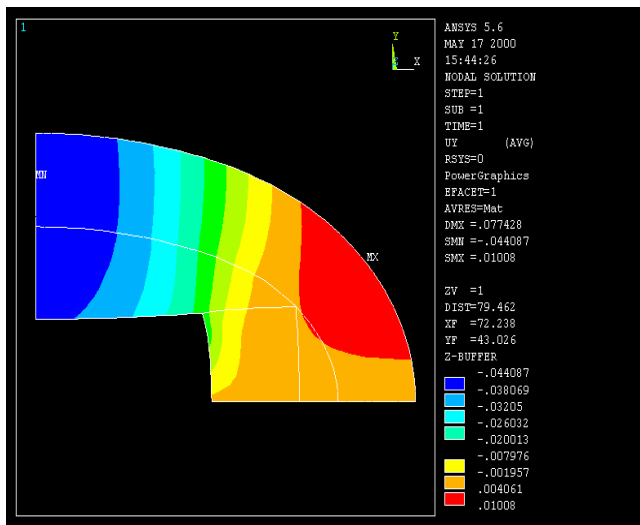

Figure 7. Deformation field in horizontal direction

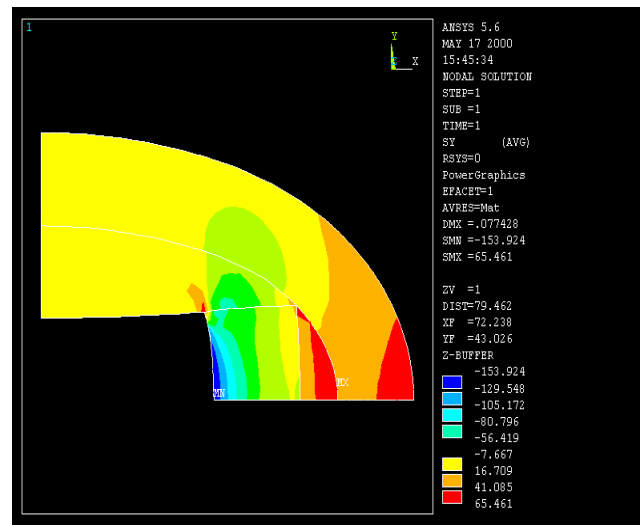Figure 8. Displacement field in the vertical direction.

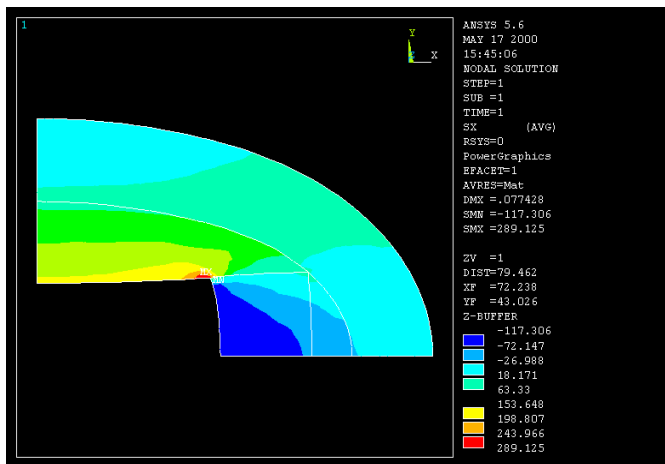Figure 10. Stress profile in the vertical direction.
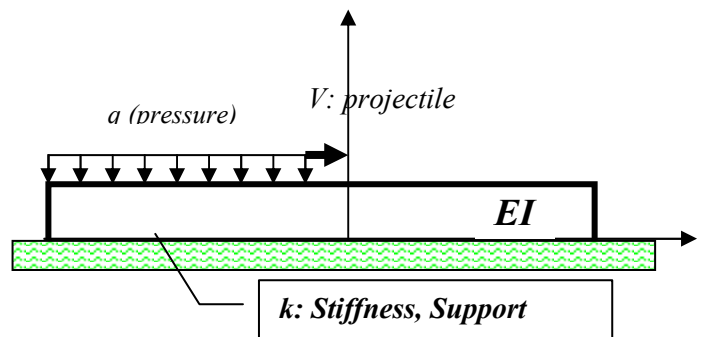

Figure 9. Stress profile in the horizontal direction.

Figure 11: Coordinates system and model of critical velocity

Table 1: Mechanical properties and geometric parameters of the rail and containment (Ref [10])

Rail (Aluminum)					
		Modulus (E)	*Thickness (h)*	*Height (B)*	*Density (ρ)*
		68.95 GPa	*12.5×10⁻³ m*	*76.2×10⁻³ m*	*2750 kg/m3*
Containment (Circular	*Steel Section)*				
		Modulus(Ec)	*Thickness (t)*	*Mean Radius (R)*	
		206.85 GPa	*12.5×10⁻³ m*	*63.5×10⁻³ m*	