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AEROTHERMODYNAMIC ASPECTS OF HYPERVELOCITY PROJECTILES

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ABSTRACT

Electromagnetic (EM) guns are being considered for a number of roles, both in the Army and Navy. They are capable of achieving launch velocities well in excess of conventional propellant driven guns. At hypervelocities of 2 km/s and greater, aerodynamic properties begin to change. In addition, heating of the projectile body and stabilizing structures can become extreme. The present paper examines EM gun launch of a notional long range projectile, giving consideration to the trajectory, aerodynamics, and thermal environment.

INTRODUCTION

Electromagnetic (EM) guns offer the potential to fire projectiles at velocities up to 6 km/s and beyond. Historically, hypervelocity EM launches have mainly been conducted to demonstrate the electrodynamic performance of the gun. Little work has been done to analyze the details of the subsequent flight. While a significant body of work exists describing aerodynamics of high velocity re-entry vehicles, it treats the interactions taking place in the upper atmosphere where air density is quite low and where trajectory shaping may reduce the effects of aerodynamic heating. For electromagnetic guns, launch generally takes place at sea level where the air density is high and aerothermodynamic problems will be extreme. While theory exists to compute the hypervelocity aerodynamics, it is rare to find work describing the flight mechanics and stability of EM launched projectiles. The present paper will examine the launch and flight of long range, EM launched projectiles.

At the Electromagnetic Launch Symposium in May 2006 in Potsdam, Germany, MG Nadeau (Commander, US Army RDECOM) challenged the technical community to consider the viability of extremely long range artillery. In particular, he was interested in a system that could send projectiles over distances equivalent to one or more time zones. Since a time zone at 30^o latitude has a width of 1400 km or so, such an undertaking is daunting. While no program exists to provide such a capability, the present paper attempts to analyze the characteristics of a projectile and launcher capable of approaching this goal.

Since EM guns are not rifled, a statically stable projectile is considered. For convenience, fin stabilization is assumed; although it is recognized that aerodynamic heating may preclude such a solution. A flare or, better yet, an active control system is preferable. The projectile is sized based on an assumed payload of 60 kg. The effects of scaled changes in projectile size and mass on range are considered. A muzzle velocity of 4 km/s is shown to provide reasonable range and is well within the demonstrated capabilities of EM railguns.

NOMENCLATURE

a_{max} = maximum in-bore acceleration
C_D = drag coefficient
$C_{L\alpha}$ = lift coefficient
$C_{M\alpha}$ = pitching moment coefficient
D = gun bore diameter
E_m = muzzle energy
I_ρ = linear current density
L = launcher length
L' = inductance gradient of railgun
M = Mach number
m = mass of projectile
m_T = launch mass
ξ, ξ' = yaw and yaw rate (rad/cal)

PROJECTILE

The projectile is an L/D = 12.3, fin stabilized cargo round, Figure 1. The body diameter is 0.200 m and the overall length is 2.46 m. There is a tungsten nose, both for the sake of stability and thermal characteristics. The outer skin is a carbon phenolic ablating surface. An active nose-cooling system will likely be required, but is not considered here. Crude allowances are made for batteries and guidance, navigation, and control that will be required for accurate fire. Six, clipped delta fins with a thickness of 0.0125 m are used. The inertial and aerodynamic properties of the projectile were estimated using PRODAS [1]. The flight mass is 227 kg, transverse and axial moments of inertia are 101 and 1.65 kg-m^2, respectively, and the payload is 57 kg. The drag and pitching moment coefficient variations as a function of flight Mach number are presented in Figure 2. At Mach numbers above 6, the coefficients vary only slightly, as would be predicted by Newtonian Theory. It can be seen that the pitching moment is only slightly negative at the high Mach numbers indicating only marginal stability. From the point of view of guidance, this situation is generally desirable.

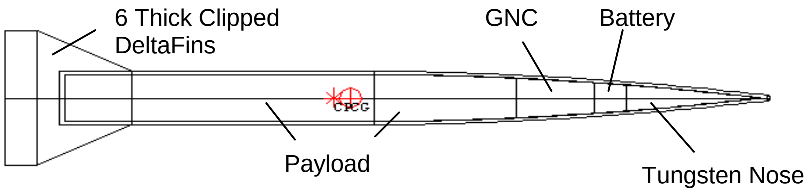

Figure 1. Schematic of Notional Projectile

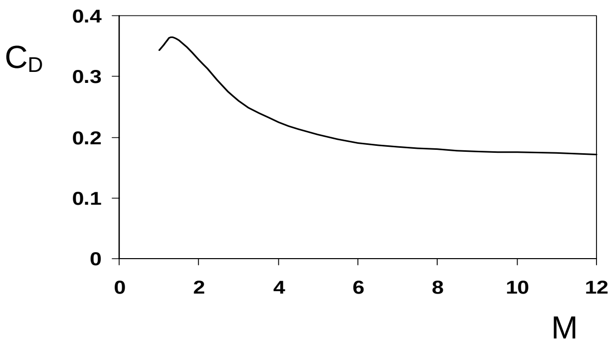

Figure 2a. Drag Coefficient

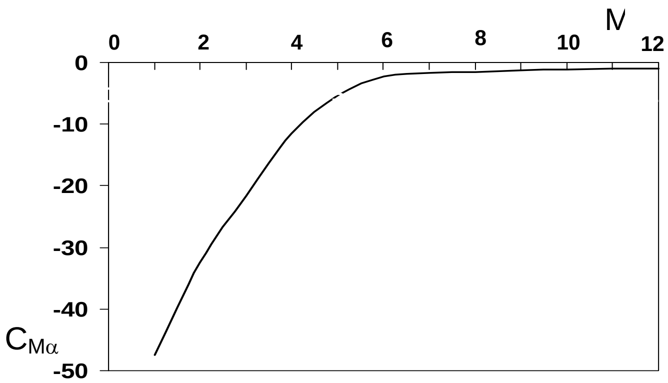

Figure 2b. Pitching Moment Coefficient

It is of interest to examine the effect of projectile mass on range. More massive projectiles have greater range; however, they also present severe problems in terms of designing a practical launcher. Cube root scaling was used to generate a family of affinely related projectiles ($D_n = (m_n/m_o)^{1/3}D_o$). Trajectories were computed based on central body theory for a curved earth. Projectile mass was varied from 1 though 1000 kg. The influence of size and mass on range is presented in Figure 3.

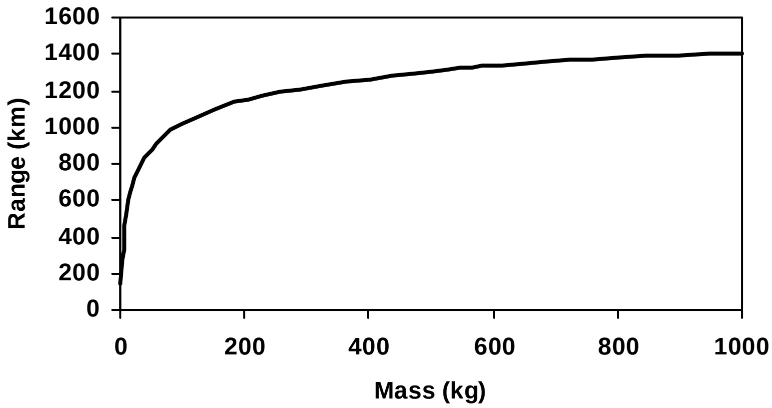

Figure 3. Range as a Function of Projectile Flight Mass for $\Theta = 40^o$, $V_m = 4$ km/s

Initially, there is a rapid increase in range with mass; however, it gradually tapers off until only modest increases in range are seen even for large changes in mass. This reflects the behavior of the ballistic coefficient (C_DA/m) which decreases as D^{-1}. It is seen that the "knee" of the curve occurs between 100 and 200 kg. The nominal design is a good choice to provide a long range (1176 km) within a relatively modest flight mass (227 kg). Further trajectory calculations show that for an elevation angle, Θ, of roughly 50^o maximum range is achieved, Figure 4.

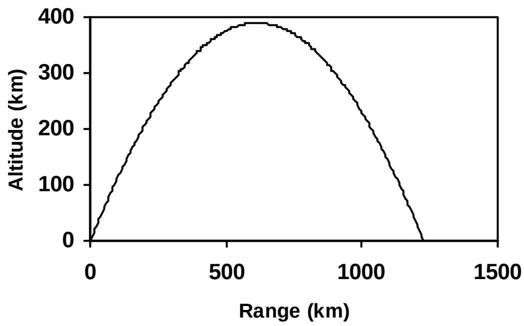

Figure 4. Trajectory for $\Theta = 50^o$, $V_m = 4$ km/s

Yaw Related Factors

Two parameters are considered: the first maximum of yaw and the aerodynamic jump. Both are considered from a "unit effects" point of view, i.e., given an initial lateral angular velocity, ξ_o', what is the response in terms of subsequent first maximum of yaw, ξ_{1stmax}, and aerodynamic jump, AJ? Simple expressions for these terms are [2]:

$$\xi_{1stmax} = [2I_t/(C_{M\alpha}\rho D^3 A)]^{1/2}\ \xi_o' \quad (1)$$

$$AJ = [I_t C_{L\alpha}/(C_{M\alpha} m D^2)]\ \xi_o' \quad (2)$$

For the notional projectile launched at 4 km/s, these are calculated to be $\xi_{1stmax} = 820\ \xi_o'$ and AJ = 58.3 ξ_o'. For comparison a conventional, L/D = 30, kinetic energy projectile [3] launched at 1.7 km/s has $\xi_{1stmax} = 639\ \xi_o'$ and AJ = 7.85 ξ_o'. If it assumed that each is launched with same initial rate, ξ_o', the yaw growths are similar; however, the aerodynamic jump of the notional projectile is significantly greater. This reflects the fact that as velocity increases, the effectiveness of fins continuously drops off. Reasonable values of yaw growth are a good thing, since it carries promise that structural integrity will be maintained. The enhanced aerodynamic jump is not desirable, but given that the projectile will be guided, this should not pose a serious problem. Another factor of interest is aerodynamic heating.

Aerodynamic Heating

A detailed aerodynamic heating analysis was beyond the scope of this effort; however, an attempt was made to estimate the thermal power density to which the projectile is exposed. The nose of the notional projectile is a hemisphere with a 0.01 m radius. Assuming a perfect gas, the isentropic flow relations give a stagnation temperature of 8244 K. This is well above the melt temperature of tungsten at 3683 K. But stagnation temperature is not the defining metric for projectile survival in a hypervelocity environment. For example, the Galileo probe of Jupiter entered the planetary atmosphere at a velocity of 47.4 km/s [4]. Assuming a hydrogen atmosphere at an ambient temperature of 123 K, the resulting stagnation temperature is 79,800 K. With an appropriate heat shield, Galileo functioned in its mission.

There are a number of sources [5-7] that permit a rough estimate of thermal power density. To shift these reentry estimates down to sea level, requires some substantial extrapolations of their data. Allen [5] gives $(dH/dt)/A = C_H \rho V^3/2$ where the heat transfer coefficient, C_H, is roughly equal to one half the total skin friction on the projectile. For the notional projectile, it is estimated that C_H = 0.011. Based on this value, (dH/dt)/A = 43 kW/cm^2. Data presented by Fay [6] and Hayes and Probstein [7] provide estimates for the peak heat flux to be 26 and 21 kW/cm^2, respectively. All of these values are greater than the peak value reported for Galileo [4], (dH/dt)/A = 13.4 kW/cm^2. Obviously, heating will provide a significant challenge and may require an active cooling approach. Alternatively, it is possible to launch at a lower muzzle velocity and use a single stage rocket motor to provide extended range. Consideration is now given to the EM railgun launcher.

EM RAILGUN LAUNCHER

McNab [8] analyzes railgun launch to space. His approach to develop a rough estimate of launcher characteristics is applied here. The notional launcher is assumed to have a circular bore with rails having an 80^o included angle, top and bottom. This yields an inductance gradient, L' = 0.5 μH/m. The gun bore diameter is 0.525 m. A ratio of average to peak acceleration of 0.7 is assumed, as is a parasitic mass ratio of 0.25. A major factor dominating the resulting physical and electrical properties of the launcher is maximum acceleration to which the projectile can be exposed. For instance, greater acceleration results in a shorter gun length; however, this also results in higher peak current, current density, and peak power. For the launch conditions of the notional projectile, V_m = 4 km/s, m_T = 303 kg, and E_m = 2.4 GJ, these parameters are presented in Table 1.

Table 1. Effect of Maximum Acceleration on Notional Launcher

a_{max} (kG)	**10**	**20**	**30**	**40**	**50**
L_{gun} (m)	117	58.3	38.8	29.1	23.0
I_{max} (MA)	10.9	15.4	18.9	21.8	24.4
I_ρ (kA/mm)	29.7	42.0	51.5	59.5	66.5
P (GW)	237	475	712	950	1187

The interplay between the gun length and current density is seen in Figure 5. The current density represents the peak current to which the rails are exposed per unit rail height. While very high values of the current density have been demonstrated in single shot events, typical multiple shot launchers have had I_ρ ~ 38 kA/mm [9]. This value varies with the rail material in question. When current density gets high, rail wear becomes a limiting issue.

For the highest acceleration, the gun length is 23 m, but the current density is 66.5 kA/mm. For reference, the Paris Gun, D = 0.21 m, K12(E), had a barrel length of

33.3 m. The D = 0.41 m, HARP Gun, had a length of 36.4 m. Both were capable of elevating, but required significant infrastructure to provide support for moving and firing. Unfortunately, the current density of 66.5 kA/mm of this 23 m long gun is well beyond present demonstrated capabilities for multi-shot launchers. To overcome this impasse, improved materials for gun rails are required.

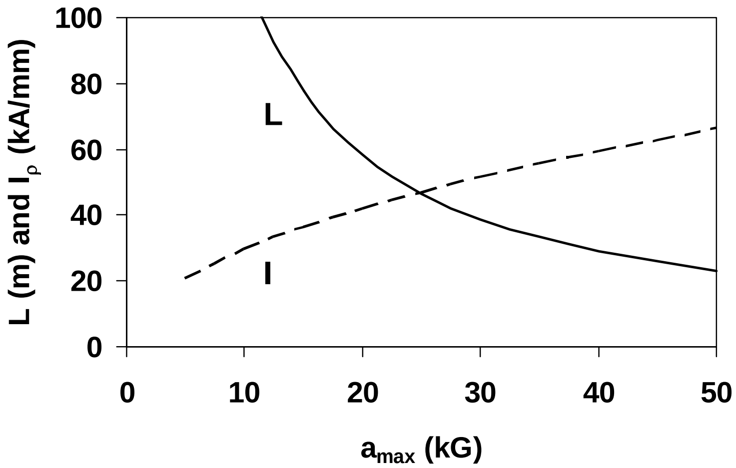

Figure 5. Railgun Parameter Variations with Peak In-Bore Acceleration

CONCLUSIONS

A notional study is presented to examine the launch and flight characteristics required to electromagnetically fire a projectile to very long range. There are significant technical problems in terms of projectile stability, aerodynamic heating, and launcher technology. Although not addressed in this paper, the pulsed power supply needed to drive the launcher is also a challenge.

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