ELECTROMAGNETIC LAUNCHERS FOR SPACE APPLICATIONS

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Abstract: An electromagnetic launcher (EML) was designed for NASA-Langley to boost large models to hypervelocity for flight evaluation. Two different concepts were developed using railgun and coilgun principles. A coilgun was designed to accelerate a 14-kg mass to 6 km/s and, by adding additional equipment, to accelerate a 10-kg mass to 11 km/s. The railgun system was designed to accelerate only 14 kg to 6 km/s. Of significance with this development is the opportunity to use the launcher for aeroballistic research of the upper atmosphere, eventually placing packages in low earth orbit with the application of a small rocket.

The 11 km/s velocity is interesting because it is exactly the escape velocity from Earth. The earth's atmosphere, however, is the nemesis, slowing an earth launched projectile. This paper will describe railgun and coilgun launch designs and suggest a reconfiguration for placement of 150-kg parcels into a low earth orbit for aeroballistic studies and possible space lab support. Each design is detailed along with the performance adjustments which would be required for circular orbit payload placement.

Introduction

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) performed a feasibility study of an EML system for a hypersonic model test facility for NASA-Langley Research Center [1]. The work resulted in a high-energy EML design to accelerate large, complex 18 in. winged aircraft models up to 11 km/s (25,000 mph) at less than 33,000 gees. Two different designs evolved which are based on railgun and coilgun concepts. Both designs make use of low current density, very long, low acceleration electromagnetic (EM) motors.

Coaxial System Description

The induction launcher system (fig. 1) is comprised of modular coaxial accelerator sections, each module being energized by its own electrical pulse machine. The payload is accelerated at an average 32,800 gees, to an exit velocity of 11 km/s by a traveling magnetic wave produced by 1.72 MA currents in each three-phase stator coil.

Figure 1. Induction accelerator

The launcher itself consists of a system of stator coils. These coils, when connected to a multi-phased power source, produce a traveling field which accelerates an armature carrying current induced by a starter coil as in figure 2. The fact that the armature has no electrical contact with the stator and rides on the traveling magnetic wave makes this induction accelerator very attractive for a space launch facility.

Figure 2. Principle of coaxial accelerator

The major components of this system are: launcher, power supplies, and projectile. The launcher has a total length of 200 m, including the starter coil. Each induction module is made up of helical coils with only the pitch or lengths differing in size. The multiple power supply concept divides the barrel in several segments, each being fed by its independent power supply. Each section of the accelerator is electrically independent, although the traveling magnetic wave continuously sweeps the entire length of the stator. The four different compensated pulsed alternators (compulsators) are operated at different frequencies initially, each frequency being slightly higher than the frequency required in that portion of the accelerator, storing a total of 3 GJ in spinning rotors. Figure 3 describes the frequency and voltage variations for each compulsator with respect to discharge time and energy stored by each module.

Figure 3. Frequency variation during discharge for compulsators

During rapid discharge of each compulsator, the kinetic energy stored in the rotors is transformed into a train of high energy sinusoidal pulses producing the traveling magnetic wave required for launch.[2] The generators must be synchronized and switched on at definite moments in time during the launch; however, this requirement is the result of a trade for energy savings achieved by energizing only the part of the launcher containing the accelerating projectile.

As the projectile passes through launch segments powered by individual compulsators, roughly half of the stored energy is released, driving the magnetic wave in the launcher. The frequency and voltage of each power supply drops 30% from prelaunch values. The projectile is handed-off to the next accelerator section, powered by compulsators with increasing frequency, with each section's wave timed to embrace the armature in a slightly retarded magnetic trough. This allows additional armature slippage into the driving wave and simultaneous build-up of armature current while traveling through the sections. The projectile is accelerated by continuous increases in coil pitch which more than makes up for the dropping frequency of the compulsators. The initial voltage varies from 8.73 kV in the first generator to 29.9 kV in the last with all values of voltage and current, root mean squared per phase.

System Analysis

The passive induction accelerator, powered by compulsators, was designed to accelerate a mass of 10 kg to 11 km/s by transferring 23% of the stored energy into the projectile during the launch.

The acceleration is relatively constant at:

$$a = \frac{v^2}{2s} = \frac{(11,000)^2}{2 \times 1.88} = 3.218 \times 10^5 \frac{m}{s^2} = 32.2 \text{ kgees}$$

The force acting on the projectile is:

$$F = Ma = 14 \times 3.218 \times 10^5 = 4.5 \text{ MN}$$

and the launch time

$$t = \frac{v}{a} = \frac{11,000}{321,800} = 34.18 \times 10^{-3} \text{ s}$$

Compulsators are presently being designed to produce voltages of 5,000 V with currents of 5 MA during millisecond pulses and store 236 MJ of kinetic energy in the spinning rotor. The 30 kV required for an 11 km/s launch is within the practical limits for rotating electrical machinery as commercial turbo-generators operate continuously at 26 kV with a 40 year amortization.

Multi-Railgun System Description

Railguns accelerate projectiles by passing a high current through an armature positioned between two rails as in figure 4. As the current passes through the armature, the interaction of the magnetic field and the current creates a force which accelerates the armature and projectile along the rail. The force is proportional to the square of the current. Using this technique, very high currents create acceleration forces leading to hypervelocity.

Figure 4. Railgun basic concept

The NASA railgun system is configured as four separate pairs of rails to reduce the current in the individual rails while producing the needed launch force (fig. 5). By using essentially four different guns to power the launcher, the lower currents will reduce rail wear. Opposing rails are connected in series to equalize current and force on the payload. Serial pairs of rails are then connected as a parallel load for the power source.

Figure 5. Multi-railgun configuration

System Analysis

To achieve a controlled surge current of 1.6 to 2.9 MA for a duration of 107 ms, the rail launcher is powered by twenty-one, 60 MJ homopolar generator/inductor (HPG/I) modules placed 11 to 16 m apart along the 180 m continuous rails as in figure 6. The power modules repeat along the launcher making a total energy of 1.26 GJ required and these modules are switched in very close to the passing armature.

Power Supply Design

The single rotor homopolar generator (HPG) is a drum type, with iron core, and an average magnetic flux density of 1.6 T. This design evolved from computer codes and appears reasonable. The rotor mass was 7,404 kg for a length of 1.24 m with a mass density of 7,860 kg/m. At the maximum angular rotor velocity, the kinetic energy stored in the HPG was 60 MJ. The machine's equivalent capacitance was 3,787 F.

Inductor Design

The inductor was designed to maximize the energy transfer from the HPG to the inductor by minimizing ohmic losses during current transfer. The major para-

eters of the inductor are

total inductance	31.32	μH
conductor volume	5.03	m^3
inductor mass	13,582	kg
ac resistance	19.6	$\mu\Omega$
number of turns	4	

A computer code was developed to analyze the multi-HPG/I powered distributed drive railgun system and the results are described in figure 7. This launch system has an overall efficiency of 20% with a launch time of 107 ms for a 14-kg mass launched to a velocity of 6 km/s. The railgun system, being the most developed of launch technologies, could make use of existing HPG power supply, inductor, and explosive opening switch technology with the disadvantage of multiple switch replacements with each launch.

Further Application for Launch Technology

This EML system was originally designed to accelerate large, heavily instrumented models to hypervelocity for free flight in a 1,000 ft flight chamber.[3] There are other applications where EML technology can play a major role. This technology is capable of boosting large aeroballistic models on longer flights in the upper atmosphere. Electromagnetic launched flights will allow heavily instrumented, free flying transition vehicles to pass from atmosphere to space at a very shallow angle, skipping back and forth, to support and evaluate aerospace plane design studies. Both manned and unmanned, real scale flying bodies will eventually be capable of horizontal take-off with long excursions into deep space as a result of the studies. Electromagnetic launches provide an expedient way to obtain hypervelocity flight information at the edge of earth's atmosphere.

To simply launch an object through the atmosphere and into space would place the projectile in a low velocity, elliptical orbit because of atmospheric drag, soon returning to the earth at a high angle. The higher the launch velocity, the greater the drag in air, especially near the earth's surface. Empirical relationships for drag coefficient (C_D) on hypervelocity tubular projectiles are developed.[4] The C_D term is expressed as a function of the mach number ($M = v/c$):

$$C_D = C_D(M) \quad 2 \leq M \leq 10$$

The resulting drag force is:

$$D = \frac{C_D A \rho v_0^2}{2}$$

where

$$A = \pi(r_o^2 - r_i^2)$$

When launched at escape velocity (11 km/s), the drag on a 1 kg, cubic shaped projectile will cause a velocity reduction of 20% in the first 16 m of flight. To overcome this problem, a higher mass, pencil-shaped projectile can be used to allow the vehicle to simply coast out of the atmosphere after launch by virtue of a larger momentum. A 300-kg projectile launched at 0.4 rad from horizontal at 10 km/s will still be traveling at 4 km/s when it reaches an altitude of 112 km/s. By using a 130 kg rocket motor ($I_{sp} = 300$ s) launched as a part of the projectile and burned at apogee, this small rocket will increase the payload's velocity to the needed 7.6 km/s placing the payload in a 112 minute circular orbit. The actual payload efficiency would then be 57%.

Figure 6. Railgun launcher

To launch a mass of the 300-kg magnitude to 10 km/s will require a total energy of 15 GJ or five of the NASA launchers described in this paper to be connected in series. The EML facility should be located at an elevation of 2,000 m to reduce the air density by 20%. This configuration would be capable of earth-to-space canister transfer of materials such as liquid oxygen, hydrogen, and construction materials such as aluminum sheet coils. These items have very high in-place value when launched with current multistage rocket technology. By packaging materials as aeroballistic projectiles for first stage EM launch, followed by a small rocket burn, the cost of this placement would rival that of overnight packages. This system would use economical utility grid power for the first lift, followed by the small rocket motor burn in the vacuum of space where rockets are most efficient. A launch system of this type would operate at significantly lower costs than shuttle supplied space construction techniques. By using EML facilities as workhorses for space transfer, the space shuttles could transfer priority cargo such as personnel and the outsized equipment that would not be feasible for reconstruction in space. Other applications for EM space launch would be the disposal of earth's nuclear waste in the sun and the deposition of small, rugged satellites in orbit.

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Figure 7. NASA-Langley multi-HPG powered distributed energy store railgun computer model