DESIGN AND DEVELOPMENT OF EXTREMELY HIGH VELOCITY
ELECTROMAGNETIC LAUNCH ACCELERATORS--GEDI PROGRAM

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Abstract: The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has designed, fabricated, and tested several advanced hypervelocity, electromagnetically launched accelerators. The work on these accelerators is part of an electromagnetic (EM) propulsion program jointly sponsored by the U.S. Army Armament Research, Development, and Engineering Center (U.S. Army ARDEC), the Defense Advanced Research Projects Agency (DARPA), and the Strategic Defense Initiative Organization (SDIO).

Present research has centered around 1, 2, or 8 m long, 12.7 mm square-bore railguns powered by one or more of the following power supplies: a 1-MJ capacitor bank driven, pulse-forming network; a 6 MJ homopolar generator (HPG) charged coaxial inductor; or one or more of six 10 MJ Balcones HPGs (BHPGs) charged coaxial inductors. Several variations of the 1 and 2 m long railguns were designed, fabricated, and tested. Railgun design parameters, development, and some test results are presented in this paper.

Parameters of primary importance in the CEM-UT railgun designs include sidewall insulator and rail materials; gun length and outer structure materials; stiffness and strength; ease of assembly and disassembly; and availability of methods for supporting, straightening, and honing the guns. Both static and dynamic aspects of railgun structural behavior were considered in the design process and are discussed in this paper.

Introduction

CEM-UT has long been involved in the development of pulsed rotating electrical generators and for the past several years has investigated, developed, and tested a number of EM launch designs. Also, as a part of this development, CEM-UT has built, assembled, and installed the Balcones hypervelocity EM gun facility. This facility utilizes the 60-MJ BHPG supply and contains six room temperature coaxial inductors, six high current fast commutating opening switches with containment, 100 kV rated connection buswork, a 40 m vacuum test range, in-flight photography and x-ray diagnostics, and the instrumentation and computer equipment necessary to provide quality data on all areas of gun and projectile performance.

For physical modeling and component development, CEM-UT has a smaller railgun facility which utilizes either or both of a 6 MJ HPG charged coaxial inductor (with cryogenic performance capability) and a 1 MJ (10 kV charge) capacitor bank driven pulse forming network. These power supplies can be operated independently or used together in a staged discharge mode. This smaller railgun facility has a 10^{-6} torr, 12 m long vacuum test range capable of being fully instrumented with all the railgun diagnostic equipment currently operated by CEM-UT. To date, 29 railgun tests have been conducted using this smaller facility and six tests have been conducted utilizing the larger Balcones facility.

To cover all the work done under the GEDI program is far beyond the space limitations of this paper. Design, fabrication, installation, and testing of the explosive opening switches, multi-MA rated buswork, power supplies, and the high vacuum test range will be reported on in subsequent reports and papers. This paper is limited to railgun development carried out over the past two years.

Railgun Development

Over the course of the railgun development at CEM-UT, a large number of parameters have been explored and evaluated. These parameters include:

- 1) rail and sidewall materials;
- 2) projectile materials, shapes, and sizes;
- 3) bore and down-range environments;
- 4) fuses and variations in the initiation of plasma armatures;
- 5) gun bore deflections, preload, and outer gun structures; and
- 6) gun length.

The basis for this research was a 1 m, 12.7 mm square-bore railgun developed by CEM-UT as part of the early GEDI program (fig. 1). This style of railgun is described in detail in previous articles [1] and provided CEM-UT with a rebuildable, precision railgun. This precision allowed performance evaluations of slight changes in the gun or gun related parameters mentioned above.

Figure 1. Square-bore railgun cross section

From these performance evaluations (performance being achieved muzzle velocity) it became exceedingly apparent that at higher current levels, one of the major gun performance loss mechanisms was bore deformation resulting in the loss of projectile driving pressure. Evidence of this loss mechanism was repeatedly seen in tests using fused quartz material as the sidewall insulators. In these tests, the

quartz fractured (due to the driving pressure) up to the point in the gun where the driving force of the plasma exceeded the structural limits of the bore material. At this point, venting of the driving pressure occurred with subsequent loss of performance. After this point, the quartz damage is much less severe, and in-gun magnetic probes, sensing armature position, show a loss of acceleration. Further evidence can be observed by examining the seal material used between insulators and rails. With the gun disassembled, black soot (which normally coats the gun bore during a shot) is seen to have been forced up into the seams and has coated the seal material in those areas where the plasma driving pressure has exceeded the bore structural limits (typically the breech, due to the high pressure of the fuse explosion and plasma initiation and the second half of a 2 m long gun where high current levels apparently produce rail deflections). Additional evidence as to bore deflections was obtained on shot #23 of a 1 m long square-bore railgun. On that shot, strain gauges were fashioned out of Metglass® and vellum paper and calibrated as to the deformation necessary to break them (fig. 2). The gauges were attached across the seams of the outer steel gun four piece clamp. After that shot, various gauges, which indicated deformation of approximately 0.51 mm, were found broken.

Figure 2. Railgun deflection measurement experimental setup

As the above evidence of bore deflections was accumulating, CEM-UT began investigating alternate gun clamping methods. These investigations resulted in a 1 m long, 12.7 mm square bore railgun, where the internal gun bore assembly was kept the same, but the structural strength of the gun was improved by a unique clamping method for applying increased preload to the bore components. The clamping is done with a casing comprised of a 12.7 mm thick, 482 MPa yield carbon steel sleeve and a series of nine 114.3 mm thick, 88.9 mm wide shrink discs spaced equally apart along the length. The sleeve was thermally fit onto the standard components (E-glass fiber-wound tube, G-10 insulators, quartz sidewalls, and molybdenum coated copper rails). The shrink disks provided radial stiffness and were also used to radially compress the steel to 90% of yield providing additional resistance to discharge loads (fig. 3). Improved gun performance (shot #24) was measured using

Figure 3. Circular shrink disc clamped railgun

this new clamping method. On the first test of the shrink disc clamped gun, 625 kA was discharged into the gun and the projectile was accelerated to 5.9 km/s. Test data indicates that the projectile accelerated through the entire length of the railgun and that a minimum amount of plasma leakage had occurred during the test.

Because the steel four piece clamp hardware existed for two 1 m and one 2 m railguns, an attempt was made to stiffen these structures. Calculations showed the design could be improved by inserting steel shim stock into the gaps between the outer steel clamp pieces and then torquing the clamp bolts to approximately 90% of the bolt yield strength. The additional stiffness is obtained because the four casing members are put into compression which is much stiffer than the bolts holding the casing members together. Calculations did indicate, however, that even with the additional bolt torque, the static rail-to-rail repulsion force for a 500 kA rail current would be approximately twice the value needed to overcome the casing compression.

A 1 m, shimmed gun was tested on shot #25. A 712 kA peak rail current caused the gun to open up and not seal the plasma armature well. A final velocity of 5.7 km/s was verified to be within 10% of simulation. Another 1 m, shimmed gun was tested on shot #26 (750 kA peak current) with similar results. Disassembly of the gun showed that extensive seam leakage of the armature plasma had occurred, and this is considered to be the primary phenomena limiting velocity on this shot.

The shrink-disc method of clamping has been used on a number of 1, 2, and 8 m railgun shots between June 1987 and the present. Though this clamping method is an improvement over the four part steel clamps, the clamping is still not adequate to prevent all plasma seam leakage. This is a result of low modulus bore and seam materials (copper, G-10, glass filled polycarbonate, etc.). The shrink disc also adds to the overall gun assembly time due to lengthy torquing requirements. For the above reasons (inadequate bore materials and clamping methods), CEM-UT is pursuing ultra-stiff railgun designs. One design, of which a gun is currently being fabricated, is described below (fig. 4):

Bore Materials

Molybdenum rails
90% alumina ceramic sidewalls;

Bore Assembly Containment

90% alumina ceramic disc pressed into a thin walled steel tube (referred to a compression sleeve);

Bore Preload

Thick walled steel pressure vessel where 241 MPa hydraulic preload is placed on the compression sleeve thereby loading the bore components.

This railgun design was pioneered by CEM-UT and a version of it is currently being tested [2,3]. Finite element analysis done on the design indicates the structure is stiffer by a factor of ten over the four part clamping structure. With this design, bore deflections can be kept to a minimum and the associated seam plasma leakage also reduced.

The bore materials are thought to be the best available at this time as to wearability and post-shot cleanup.

Figure 4. Hydraulically clamped railgun

Railgun Testing and Results

Though a good number of railgun tests have been done during the GEDI program, the tests were often done in conjunction with some new facility or diagnostic equipment checkout. Tests of this nature, often added complexity or uncertainty to a railgun shot but were necessary to bring on-line the many pieces of hardware or instrumentation needed to allow extremely high energy shots with reliable instrumentation and controls. Because of this, a first class facility for railgun testing is now in place for repetitive railgun testing.

The typical instrumentation now in place for a 1 m railgun test includes the following:

1. calibrated Rogowski current monitoring system with coils on the individual generator busbars, inductor busbars, the opening switches, the current collection turret, and the gun breech buswork;
2. high voltage probes on each generator and switch, buswork collection turret, gun crowbar/breech, and muzzle;

3. actively integrated B-dots for measuring gun current and armature position;
4. four flash x-ray heads with independent timing delays;
5. CW x-ray fence for detecting projectile exit from bore and starting triggering sequence of flash x-ray system;
6. muzzle flash and target impact flash photodiode detectors; and
7. an impact make screen target.

Data is collected by intermediate modules organized in CAMAC crates which are controlled by a DEC MicroVax Work Station II, which in turn, is networked with a controller DEC VAX 750 for data archiving and data graphic production. The data collection system can capture up to 128 channels of data at varying sample rates. Also, instrumentation and controls are in place for the various facility power supplies [5,6].

1-m Gun Results

As mentioned previously, a new shrink disc clamping method was done for shot #24. The test was done using a peak discharge current of 625 kA. Preshot simulation predicted a final velocity of 6.2 km/s for the 2-g projectile.

Magnetic probes close to the bore of the gun show that the projectile's average velocity between $x = 0.674$ m and $x = 0.894$ m was 5.4 ± 0.17 km/s. Extrapolating the velocity curve from the probe to the end of the gun indicates a final projectile velocity of 6.1 ± 0.19 km/s.

Multiple flash x-ray photos of the projectile show that the projectile had fragmented, and damage at the muzzle of the gun indicated that the fragmentation had occurred at the muzzle. From the x-ray photos, the velocity of the largest projectile fragment was found to be 5.6 km/s. A smaller fragment was seen in the photos moving at 5.9 km/s. Velocity screen data indicates another fragment moved at about 6.3 km/s.

Figures 5, 6, and 7 show pertinent data collected and plotted for shot #24.

Shot #24 Summary

Projectile

Size - 12.67 x 13.23 x 12.57 mm
L/D - 0.95
Mass - 1.975 g
Placement - 34.93 mm from breech
Material - Polycarbonate annealed

Armature

Mass - 0.058 g
Material - 0.127 mm aluminum shim stock

Total Accelerated Mass

- 2.033 g

Insulator Material - Quartz glass

Rail Material - 0.51 mm thick molybdenum flame-sprayed on copper

Inductance Gradient - 340 nH/m

Predicted Exit Velocity - 6.15 km/s

Predicted Exit Time - 505 μ s from commutation

Figure 5. Gun current, in-bore integrated radial magnetic probe signals, and voltage probe signals for shot #24

Maximum Velocity
 B-probes - 5.5 km/s
 Screens - 6.3 km/s
 Flash x-ray - 5.6 to 5.9 km/s (fragments)

Homopolar Generator and Capacitor Stores (9)
 Charging Voltage - 8 kV
 Initial Speed - 4,500 rpm
 Peak Current - 625 kA
 Total Dissipated Energy - 860 kJ
 Projectile Kinetic Energy - 31 kJ

Vacuum - 1.8×10^{-5} torr (pre-shot)

8-m Gun Results

As discussed earlier evidence indicated that at high current levels the falling off of performance was the result of the gun bore seams opening up. Two strategies were prepared to overcome this performance loss: 1) build long railguns (5 to 10 m) using conventional materials and technology and operate these guns at modest current levels (400 kA) and 2) build the ultra-stiff guns designed as per previous discussion.

An 8 m long, 12.7 mm square-bore railgun was built using glass filled polycarbonate sidewalls and copper rails. The assembly was clamped as per the shrink disc method discussed earlier. Due to the

length, a very stiff straightening structure was fabricated to hold and straighten the gun. Also the structure contained a specially built pneumatic honing machine which was used to hone the gun to a 0.025 mm bore tolerance. The 8 m gun test was powered by four BHPG charged inductors producing a gun current of approximately 450 kA.

The projectile accelerated as predicted during the first 3 m of the gun to a velocity of 6 km/s, but appeared to coast out of the bore without any further acceleration after the 3-m mark. Magnetic probe data indicates that the armature driving the projectile accelerated as predicted to a velocity of 6 km/s at which point it was 3 m into the gun. At this time, the current appeared to commutate into a precursor arc which was positioned at about 6 m into the gun. The loss of current in the armature behind the projectile caused this arc to become diffuse and not well defined and carried little current. At projectile exit, as determined by muzzle volts and muzzle flash signals, current was commutated back into the diffuse plasma cloud which remained behind the projectile. Shortly following this time, the gun current was crowbarred and the arc accelerated out the bore using the energy stored inductively in the rails to sustain a weak current. The 8 m gun will not be tested again until this current behavior has been thoroughly analyzed and some plan formulated to prevent the precursor and the restrike arcs from occurring.

Figure 6. Total current and individual store currents for shot #24

Figure 7. Inbore axial magnetic probe signals for shot #24

Conclusions

From the gun tests performed to date, the major obstacle confronting railgun performance appears to be one of structure. A new ultra-stiff railgun is being built that should address the structure problem. Should this gun design prove to work, as per simulation, the 6 km/s limit barrier would be broken. At that point, the more subtle problems of ablation and friction can be more carefully examined and designs formulated to overcome those performance limits.

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