Rapid Fire Railgun For The Cannon Caliber Electromagnetic Gun System

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CANNON CALIBER ELECTROMAGNETIC LAUNCHER

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ABSTRACT

The Center for Electromechanics at The University of Texas at Austin (UT-CEM) designed and fabricated a rapid fire railgun launcher. A single-shot prototype was tested for the Cannon Caliber Electromagnetic Gun (CCEMG) system. Three, five round salvos of 185 g launch packages are to be accelerated to 1,850 m/s at a rate of 5 Hz. The 2.25 m long launcher has a 30 mm round bore equivalent rectangular geometry and is water-glycol cooled. Rapid fire operation is achieved by driving the launcher with multiple 835 kA peak pulses provided by the CCEMG compulsator. The launcher is a series augmented railgun and has a demonstrated breech efficiency over 50%.

A high CCEMG system efficiency is in part due to the use of a solid armature and is enhanced by having a structurally stiff railgun. Historically, a railgun's stiffness was proportional to its weight. Laboratory based railguns that have respectable mechanical properties have required massive structures that are nowhere near meeting the requirements of future vehicle integration and weaponization. The CCEMG railgun design incorporates a directional preloading mechanism, ceramic sidewalls, and a composite overwrap which together give it a structural stiffness dominated by a high modulus ceramic. The overall mass of the launcher is 273 kg. These characteristics make the cannon caliber launcher one of the most “fieldable” railguns built to date.

INTRODUCTION

The Cannon Caliber Electromagnetic Gun System (CCEMG) design represents the culmination of two decades of electromagnetic launcher research in the areas of pulsed alternator, railgun and integrated launch package (ILP) development. Although this paper focuses on the design and initial testing of the CCEMG railgun, the power supply[1] and ILP must be acknowledged for their contribution to the gun's final configuration. Early in the design process, an optimization code called EXCALIBER was utilized to identify the ideal system parameters and launcher geometric and electrical configuration[2]. The resulting railgun design parameters are listed in **table I**. The railgun is 2.25 m long with an augmented turn in series with the main rails. Only the first 1.85 m of the gun is augmented and the gun has an muzzle switch "tap" located at 1.9 m. The railgun bore geometry is rectangular; 1.75 cm x 3.94 cm (**fig. 1**).

The CCEMG railgun incorporates several unique features: ceramic sidewalls, directional preloading and liquid cooling. A developmental mentality was adopted by the program to evaluate the gun's structural design while studying the performance of several ILP concepts. As a result, two single-shot guns were built (referred to as launchers IIA and IIB) in addition to a water-glycol cooled, rapid-fire gun (launcher III). This paper presents test summaries and general performance observations for launcher IIA performed at both the Center for Electromechanics at The University of Texas at Austin (CEM-UT) and U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, MD.

DESIGN

In addition to railgun structural and electrical design requirements, the Cannon Caliber gun design considerations include thermal management, bore wear, and weight. For the interested reader, reference [3] presents specific details of the electromagnetic (EM) and thermal design as well as the launcher component development. Launchers IIA and IIB are identical to the multi-shot launcher with the exception of coolant passages and deceleration guide required for autoloading. A peak gun current of approximately 830 kA for 15 rounds requires active cooling between salvos by coolant passages located in both main and augmenting rail sets.

Directional preloading mechanisms called "flatjacks" located between the main and augmenting rails (**fig. 1**) are utilized to counter electromagnetic loading and maintain a compressive state in alumina ceramic sidewalls. The success of the launcher design depends heavily on the flatjacks ability to apply a pressure to the main rails so that the ceramic sidewalls (AD-96 alumina) remain in compression throughout the discharge. This results in an extremely stiff design. Preload is reacted against a filament wound composite overwrap composed of 82%, 90° graphite fibers and 18%, 0° fiberglass. The overwrap reacts the preload plus a fraction of the EM loading and provides stiffness to the launcher in the axial direction. These features give the launcher a peak bore growth of 0.2% at full electromagnetic loading and an overall weight of 273 kg.

The flatjacks are formed by a series of cold drawing operations on a seamless Inconel 718 tube. Manifolds and fill tubes are welded to the ends. The flatjacks are pressurized to 138 MPa for a full current shot and must endure a displacement of approximately 1.3 mm. Inconel 718 in the annealed condition fulfills the strength, ductility, and non-magnetic requirements of this application.

Chromium copper (C18200) was chosen as the rail material because of its strength (310 MPa yield), conductivity (82% IACS), relatively low cost and its dimensional stability. The rails of launcher IIA have to date experienced a total of 50 shots. Coolant passages in launcher III are formed from 8 mm holes (two parallel) drilled the length of the main and augmenting rail forgings. To attain the launcher's high breech efficiency, the main rails are slit (1.6 mm wide on 3.2 mm centers) transverse to the gun's axis to the mid-point of the ceramic sidewall. This region of the main rail is required for structural purposes but is detrimental to performance and therefore is slit to minimize its current-carrying ability.

CEM-UT TESTING

Testing of single-shot launcher IIA has been performed both at CEM-UT and ARL. A total of 11 shots were performed at CEM-UT and ARL has shot 39 times. Testing at CEM-UT was successful in verifying the predicted mechanical and electrical performance of the launcher. Launcher IIA was powered with the 1 MJ/pulse, iron core compulsator (ICC).

A total of 11 shots were performed with a gradual increase in system energy. **Table II** lists the system parameters and projectile performance for selected CEM-UT and ARL tests. Prior to electrical testing, bore straightness was measured before and after flatjack pressurization to determine the flatjacks effect on straightness. Very little change in the bore straightness was observed, indicating that a uniform amount of axial strain was being applied to the structure, or the flatjack axial strains have little effect on the structure. The peak deviation from a straight line for either the sidewall or rail direction was 0.2 mm. Honing of the bore was performed between shots to remove armature deposits with no attempt to remove rail material; the bore dimensions remained consistent throughout testing. The bore straightness was checked after CEM-UT shot #11 and again there was no significant changes in bore straightness as compared to the initial measurements. CEM-UT range diagnostics consisted a single set of orthogonal muzzle x-rays, velocity screens and a single yaw card located at 6.4 m. Launcher instrumentation included b-dots, a flux ruler and voltage and current measurements. Several unsuccessful attempts were made at measuring flatjack pressure transients with a PCB pressure transducer.

Highest performance occurred on UT-CEM shot #7 which has a peak current of 552 kA. Voltage limitations of the ICC combined with the inductance of the augmented launcher prevented testing to higher current levels. Although the structural limits of the gun could not be fully characterized, its electrical insulation was tested by the multiple open circuit cycles of the ICC after a shot. During shot #11, an insulation flaw was identified within launcher IIA. Post-mortem examination of the launcher revealed that the launcher insulation system was weak.

Launcher IIA was repaired by pumping the lower failed flatjack with a filled epoxy while the upper flatjack was depressurized to allow the epoxy in the bottom jack to cure at maximum displacement thus limiting displacement of the upper jack. Once the epoxy had cured, the remaining flatjack was repressurized to 103 MPa. The electrical resistance between rails was deemed adequate for performing single-shot tests using capacitor banks and launcher IIA was shipped to ARL.

A number of modifications were made to the electrical insulation design of launchers IIB and III. These include: thickening the mica insulation, adding a composite insulating barrier between the flatjack manifold region and the augmenting rails, applying Limitrak insulating enamel to both sets of rails, and adding an additional fiberglass layer to the bore of the composite overwrap. In addition, several intermediate dc and transient hi-pot tests were added to the assembly procedure.

ARL TESTING

Test Objectives

The test objective was to experimentally verify launcher and ILP performance in single-shot mode of operation. Testing was planned such that an abundance of relevant data could be obtained early in the program without placing the hardware at unnecessary risk. Thirty-nine rounds have been shot from launcher IIA at ARL. Tests can be grouped into component characterization (shots 1-9), armature development (shots 10-16), launch dynamics (shots 17-27), pseudo multishot (shots 28-32), and peak performance (shots 33-39). Results discussing ILP performance are reported elsewhere.[4]

Range Facility and Power Supply

Testing took place at the EM Facility, Transonic Range, Aberdeen Proving Ground (APG) MD. The Facility consists of a (upgraded after shot 27) 1.55 MJ capacitor-based pulsed power supply (PPS) with a 222 m free-flight range.[6] The PPS is comprised of eight banks, each with the flexibility to be charged to different initial voltages as well as to be triggered independently in time. Maxwell Laboratories and General Electric capacitors are used throughout the PPS. Each bank is nominally 200 kJ at a rated maximum charge voltage of 10 kV. Each bank is connected to a common bus through a D-size ignitron (NL-2888A) and a nominal 10 μH inductor. Stacks of diodes are connected across each bank output to prevent voltage reversal across the capacitors. Four banks use 12 PowerEx RA204420 diodes each while the remaining banks use International Rectifier semiconductors. The PPS, under short-circuit load conditions, can provide a current pulse with a 375 μs rise time with a transfer admittance of 120 kA/kV. The current decays with a time constant of nearly 8 ms. With launcher IIA as the electrical load, peak current is estimated to be 850 kA, occurring at 460 μs and a time constant of 3 ms. Launcher IIA installed in the EM facility is shown in **figure 2**.

Instrumentation to monitor and assess ILP performance consists of bore-sighted yaw cards, multi-station orthogonal flash x-ray with fiducial cable, radar, smear and high-speed camera, and realistic armor targets located 222 m downrange from the launcher. Instrumentation to assess launcher performance includes b-dots, flux rulers, and current and voltage measurements. Observations are made with regards to muzzle motion and flatjack pressure.

Attaining CCEMG system performance is first and foremost dependent on ILP structural integrity, and subsequently, subprojectile accuracy. One factor affecting both is the deviation of the bore centerline. The "straightness" measurement is made routinely on conventional guns and this data is often used to assess the quality of the gun. Often, launchers exhibiting large deviations from centerline are not used for projectile range testing. Railguns offer two distinct planes for centerline: one for the rail plane and the other for the insulator plane. The “straightness” for launcher IIA in both the rail and insulator planes, has been routinely measured by the Aberdeen Test Center, ATC (formerly Combat Systems Test Activity, a tenant activity at APG, MD) throughout the duration of all testing. On average the straightness for launcher IIA is the same for a similar caliber conventional gun. However, its deviations along the direction of projectile travel are smoother than those exhibited in launcher IIAs. The deviation at the muzzle of launcher IIA is upwards in the rail plane and towards the left in the insulator plane (looking downrange). Over 90% of the ILPs have had impacts biased towards the left side of launcher line of fire. On the other hand, 75% of the rounds have exited the launcher with impacts above the launcher line of fire. The nose of the projectile at muzzle exit is oriented downwards for roughly half the shots. Phenomena at the rail/armature interface near exit may overwhelm the dynamics offered by bore straightness in the rail plane for these velocities.

Prior to all the shots the launcher bore has been cleaned by pushing a lapping tool through the bore (i.e. honed). Mineral spirits is used as a cleaner and lubricant with the tool. The lapping tool consists of opposing steel wedges with diamond faces and locked to a preset width. The width has been set to only remove any aluminum deposited on the rail surfaces. Consequently, very little copper rail material has been removed. After the launcher is honed the bore is wiped with paper towels soaked in alcohol. In the pseudo multishot tests (shots 28-32) the bore was not maintained between the 5 shots. No unusual launcher or projectile behavior was observed.

The flatjack pressure is nominally at 97 MPa for the primary jack and 41 MPa for the secondary jacks. On shot #39, the primary flatjack successfully held 128 MPa. The pressure is measured with a standard pressure gage having increments of 0.7 MPa. Typically, immediately after a shot the pressure gage reads an increase of roughly one-half an increment and subsequently settles down to its original reading. It is uncertain as to the significance of this observation since the pressure increase is only one-half an increment.

Armature performance is partially dependent on mechanical preload placed on the armature contacts. The preload is provided by a tapered interference fit between the armature and the bore rail surface. Optimum preload is difficult to calculate but has been estimated to be 13.34 kN for this armature[2]. Clearly, no preload will result in an immediately arcing contact and too much preload will result in immediate structural failure. Armature interference is obtained from knowledge of the rail to rail dimension. For all the shots this has been estimated by measuring the rail to rail dimension set by the hone. This technique has a measurement error on the order of 0.13 mm. An indication of the preload placed on the armature contacts can be assessed by measuring the amount of force it takes to insert the ILP in the bore. The insertion force is measured by converting the pressure gage reading in a hydraulic cylinder as the round is inserted into the breech, roughly 30 cm from the rear face of the launcher. Lowest and highest recorded values for insertion force throughout the testing are 2.24 kN and 7.97 kN respectively. No anomalous armature behavior has been noted for these shots. In fact, the CCEMG design velocity was exceeded using a 100 g tandem contact slug with an insertion force of 2.79 kN (shot #7, 1,886 m/s). Afterwards, the bore rail surfaces were video taped and no visual evidence of gouging on the rail surface was observed.

After shot 32, the rail to rail dimension was accurately measured as a function of launcher length by ATC. The nominal rail-to-rail dimension is 3.73 cm with a +0.03 mm variation. Similarly, the nominal rail-to-rail dimension was measured after shot #39 to be 3.73 cm, with a +0.05 m variation. No trend in the variation was noted as a function of launcher length.

LAUNCHER PERFORMANCE

The highest launcher current to date is 766 kA and occurred on Shot 39. Also on this shot the muzzle current was also the highest at 384 kA. Afterwards it was found that the G-10 plate at the muzzle that supports the secondary flatjack and plumbing had separated axially from the carbon fiber overwrap. Since this launcher was not designed to sustain such large forces at the muzzle it is not surprising that this structural deformation occurred. None-the-less, the round successfully flew and impacted the target downrange. Launcher current is plotted in **figure 3.** In order for full launcher and ILP performance to be realized, prior testing incorporated an explosively activated closing switch connected through stainless steel buswork at the muzzle “tap”[7]. Shots 33 through 38 have employed the switch. On the last shot (shot 39) a peak armature current of roughly 423 kA was successfully commutated into the muzzle switch. The launcher current just before exit was 355 kA while the current flowing in the armature was reduced to 134 kA. Structural deformation at the muzzle switch buswork was observed and is shown in **figure 4**. Light and sound signatures associated with a large exit current were significantly reduced. The average time for full commutation to occur is 460 μs ±70 μs. Launcher, switch, and armature currents for shot #38 are shown in **figures 5 and 6**, respectively.

The largest amount of rail wear occurs at the muzzle, primarily due to the large currents flowing through the launcher when the ILP exits the launcher. The wear at the muzzle end of the launcher has been monitored and found to be less than 1 mm per rail occurring over the last 10 cm of rail length. This erosion accrued during the five pseudo-multishots with ILP exit velocities of 1,100 m/s. The erosion of the rail at 13 cm in from the muzzle end of the rail was only 0.10 mm per rail.

The conversion of energy supplied to the breech to kinetic energy at the muzzle increases as peak current is increased. The highest efficiency was obtained for shot 39 with a value of 35% and a launch velocity of 1,785 m/s. This value also includes the magnetic energy remaining in the circuit since current is not zero when the ILP leaves the barrel. The magnetic energy is transferred into additional ohmic heating in the resultant arc and conductors. If this energy could be converted into a charge on the capacitor banks (much like the compulsator rotor would spin up at projectile exit) the net efficiency would increase to 45%. The efficiency of converting the stored capacitive energy to kinetic energy is 22%. For a constant launch velocity all the efficiencies are found to decrease by a few percent for the shots that used a 100 g launch mass. For all 50 shots, the launcher inductance gradient has been computed from the measured current and velocity and found to be 1 μH/m.

Since the gun had been rendered unusable after ARL test #39, it was decided to pressurize the remaining flatjack to failure to determine its upper design limit. In addition, a metallurgical examination of the bore components is warranted considering the rails and sidewalls have endured 50 shots without significant honing.[8] The upper primary flatjack pressure was pumped to 30 ksi without failure. Pressurizing was stopped at 30 ksi in the event the high pressure would damage the augmenting rails which needed to be salvaged for a future launcher.

Launcher IIA disassembly proceeded with the breech. Threaded jacking holes were machined into the G-10 breech plates to facilitate their removal. Nothing out of the ordinary was observed during this process. Breech cross-over conductors and hexapolar cable connections showed no signs of arcing or any form of contact degradation. Next, the titanium muzzle switch mounting hardware was removed from the muzzle end and the muzzle switch conductors were pulled out. The muzzle switch conductor contacts showed no signs of contact problems. The composite overwrap was removed by milling full length and depth axial slots through the overwrap. The augmenting rail, flatjacks and main rail bonds were intact. The electrical short between the lower augmenting rail and lower primary flatjack (and subsequent flatjack failure) from CEM-UT test #11 was found to have occurred at the muzzle manifold weld, as surmised.

Main rail separation proceeded by removing the mica overwrap. The main rail assembly was placed on the precision assembly I-beam and heated to 400°F for approximately two hours. While hot, a separation force was applied to the breech end. Apparently, the sidewalls had several cracks which created the stress concentration and caused the ceramics to split when pulled on. The cracks (both top and bottom rail) start about 0.2 m in from the armature insertion point and initiate at the rail planes and propagate outward into the ceramic. The cracks last for only 0.1 m of axial length. The cracks have aluminum in them indicating they were present prior to pulling the rails apart.

The ceramic appears to have a small step (0.05 mm) possibly created by sidewall honing; it is difficult to believe that this material ablated away, especially at the breech. This step is where the cracks initiated. EM loading was probably a factor in propagating the crack however peak loading should have occurred at the insertion point for the ARL tests. At least one crack (with aluminum in it) was observed to have propagated in the rail-to-rail direction. It is possible that the crack may have been created by an insufficient flatjack preload thus creating a tensile stress condition in the sidewalls.

The flatjack to augmenting and main rail bonds were very good. However, the ceramic to main rail bonds were found to be marginal. This could be the area where axial slip was occurring thus resulting in deviations in straightness from shot-to-shot. The cracks could also have provided a slip plane to relieve the residual axial assembly stresses.

In general, the rail bore surfaces revealed very little damage (other than muzzle wear). The entire bore was coated with aluminum however there was no sign of pitting or gouging.

CONCLUSION

An overview of the CCEMG launcher design has been presented and testing performed at CEM-UT and ARL has been described. The design successfully incorporates directional preloading (flatjacks) and ceramic sidewalls which give the launcher its extremely high stiffness and low weight. A total of 50 shots have been performed. The initial tests have demonstrated breech efficiencies over 50%. ILP accuracy in the horizontal plane is largely due to the dimensional stability offered by the ceramic sidewalls, flat-jacks, and launcher design. Controlling the physics offered in the rail-plane may lead to EM launchers with enhanced overall accuracy and dispersion. In addition, these tests have demonstrated the durability of the launcher's structural design in the presence of high and multiple muzzle currents and operation with a single flatjack.

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REFERENCES

[1] J.R. Kitzmiller, et al, "Optimization and Critical Design Issues of the Air Core Compulsator for the Cannon Caliber Electromagnetic Launcher System (CCEML)," 7th EML Symposium on Electromagnetic Launch Technology, San Diego, CA, April 20-24, 1994.

[2] J.H. Price, et al, "Discarding Armature and Barrel Optimization for a Cannon Caliber Electromagnetic Launcher System," 7th EML Symposium on Electromagnetic Launch Technology, San Diego, CA, April 20-24, 1994.

[3] M.D. Werst, et al, "Design and Testing of a Rapid Fire, Lightweight, Ultra Stiff Railgun for a Cannon Caliber Electromagnetic Launcher System," 7th EML Symposium on Electromagnetic Launch Technology, San Diego, CA, April 20-24, 1994.

[4] A. Zielinski, K. Soencksen, D. Webb, and P. Weinacht, "Integrated Launch Package Performance in the Cannon Caliber Launcher," submitted to the 8th EML Symposium, Baltimore, MD, April 1996.

[5] M.D. Werst, J.R. Kitzmiller, and A.E. Zielinski, "Rapid Fire Railgun for the Cannon Caliber

Electromagnetic Gun System," presented at the 10th IEEE Pulsed Power Conference, Albuquerque, NM, July 10-13, 1995.

[6] A. Zielinski, "Preliminary Assessment of Recoil in a 15 mm Solid Armature Railgun," proceedings of the 11th Electromagnetic Launcher Association Meeting, September 1993, Huntington, W VA.

[7] R.L. Sledge, J.J. Hahne, "Experimental Data on High Power Explosive Opening and Closing Switches at CEM-UT," Seventh IEEE Pulsed Power Conference, Monterey, CA, June 11-14, 1989.

[8] S. Kerwign, "Metallurgical Post Mortem Analysis of the Cannon Caliber Electromagnetic Gun (CCEMG)," submitted to the 8th EML Symposium, Baltimore, MD, April 1996.

Table I. Cannon caliber railgun design parameters

Performance	
Launch package mass	185 g
Muzzle velocity	1,850 m/s
Muzzle energy	315 kJ
Launcher energy density	1.16 J/g
Inductance gradient	1.1 μH/m
Peak current	835 kA
Number of salvos	3
Rounds/salvo	5
Firing rate	5 Hz
Time between salvos	2.5 s
Physical	
Railgun type	Series augmented
Bore dimensions	Rectangular 17.5 x 39.4 mm
Overall length	2.25 m
Augmented length	1.85 m
Stiffness at peak current	0.2% deflection
Coolant	Water-ethylene glycol
Weight	273 kg