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AUGMENTED RAILGUN

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Abstract: The Center for Electromechanics at The University of Texas at Austin (CEM-UT) is currently in the manufacturing phase of a 29-month program to build and test a laboratory based small caliber electromagnetic (EM) launcher and compulsator power supply. The goal of the EM launcher is to deliver a three shot projectile salvo at 10 Hz. The muzzle energy of each 32-g projectile is 64 kJ, which yields an exit velocity of 2,000 m/s. A full-scale, 0.60 caliber, 1.6 m prototype railgun has been built and is currently being tested at CEM-UT. This augmented railgun incorporates a low mass, high inductance gradient ($1.25 \mu\text{H/m}$) design. High strength stainless-steel laminations support the primary and augmenting rail package in a compact and inherently stiff design. Rail erosion is minimized by the use of molybdenum for the primary rails. Copper is used for the end turns and augmenting conductors to ensure reliable bolted connections and to reduce the overall gun resistance. The laminations are insulated using epoxy adhesive and held in compression using an overwrapped composite preload tube. The entire gun weighs less than 100 kg and will be mounted to a recoil mechanism when fired from the compulsator power supply.

This paper presents the design for the 0.60 caliber augmented, laminated, solid-armature railgun. Included is the discussion of the magnetic pressure distribution and heating on the molybdenum and copper conductors, and gun stiffness as predicted by finite-element analysis. The inductance gradient is calculated and correlated to experimental results. The materials selection, fabrication details, and insulation methods are also discussed. Finally, gun performance is presented through experimental data collected from testing solid armature projectiles.

Introduction

The goal of the small caliber launcher and compulsator power supply is to advance EM launch technology from the laboratory into the field. Both the railgun and compulsator are designed with the intent of achieving the highest power density ratio possible while utilizing existing technology. The design of the air-core compulsator is presented in another paper in these proceedings [1].

A large data base of information regarding railgun construction techniques, rail materials, insulation methods, and structural support methods can be accessed from both CEM-UT and other laboratories. While this data base was helpful in the design of the small-caliber railgun, several key technological issues had to be resolved prior to full-scale gun construction. These issues were resolved through EM analysis, finite element analysis, and laboratory-

based experiments. Materials selection and insulating techniques were chosen with the goal of minimizing gun weight, and maximizing gun stiffness while maintaining good insulation practices.

Launcher Design Issues

In addressing the issues of gun weight stiffness and performance, several key design goals were identified including:

1. The design of a viable launcher which weighed under 150 kg.
2. A breech connection design that would facilitate the use of an autoloader. This required the breech to be as thin as possible to reduce the autoloader stroke as much as possible.
3. Rail materials which would minimize wear and the required gun bore honing between shots.
4. The selection of a sidewall material that would resist wear and gouging.
5. Maximization of the stiffness of the gun to preclude unnecessary armature wear.
6. The selection of materials which are readily available and easily machined or fabricated.

The above design goals were bounded by several key constraints placed on the launcher design. The most significant of these constraints included:

1. The gun must be compatible with the anticipated compulsator power supply load specifics. The gun inductance gradient was set at $1.17 \mu\text{H/m}$ minimum when the compulsator/gun combination was optimized. This led to the use of an augmented launcher.
2. The active gun length was set at 1.6 m.
3. The gun bore was limited to 0.60 caliber.
4. The gun should be capable of a three shot salvo.
5. The gun must withstand a peak voltage of 2.2 kV between shots

Preliminary Armature and EM Gun Testing

In satisfying the design goals and constraints, several technological concerns had to be overcome. The first concern was armature survival. Due to the bore size, the armature contact area on the rails is limited. This resulted ultimately in a high current density at the rail/armature interface. A 1.0 m long augmented railgun was built and tested using the 1 MJ capacitor bank power supply at CEM-UT. This testing iterated the armature design until a satisfactory armature survival rate was established. Some details of this testing are presented in a companion paper in these proceedings [2].

The second concern was the use of polyurethane as a sidewall material. In the same 1.0-m gun, polyurethane was used successfully as a sidewall insulator. The material provided a durable, smooth surface which withstood full-energy discharges from the railgun. The polyurethane is also desirable because it can be potted into the barrel after the gun is assembled. It can also be easily repaired in the event of unplanned degradation after a shot.

The final concern was the high current density augmenting turn connections. Due to the laminated gun design and the effort to minimize gun weight, both the muzzle and breech augmenting end-turn connections were designed with high current densities. Analysis determined that the breech end-turn connection would have to pass 596 MA/m² and an $\int I^2 dt$ of 120 MA²-s. A breech end-turn mockup was fabricated and successfully tested on the capacitor bank power supply. Although the $\int I^2 dt$ could not be fully tested, the joint did carry a current density of 752 MA/m² and an $\int I^2 dt$ of 60 MA²-s.

EM Gun Rail Design

Having successfully demonstrated these important design goals, the full scale gun design commenced. An early step in the gun design was to select a rail cross section which satisfied the design goal inductance gradient of at least 1.17 $\mu\text{H/m}$. A CEM-UT code (LCODE), using a method similar to Leuer [3], was used to estimate the gun inductance, find the magnetic pressure distribution, estimate rail heating, and calculate the rail repulsion forces to be used in performing structural analysis. LCODE assumes an infinite element conductivity and a step function input for the current. LCODE has been extensively tested against analytic solutions and measured values. The assumptions used in LCODE result in a worst case pressure loading and heating for the conductors. Several cross sections were analyzed before arriving at the final design. The rail cross section selected for use in the small-caliber gun is shown in figure 1. The circular shape allows simple fabrication of the steel laminations as well as assembling the laminations over the rail assemblies.

Figure 1. Laminated, augmented gun cross section

Component Materials

Molybdenum was selected for the primary rails due to its high strength and stiffness, satisfactory conductivity, low wear, and availability. ETP110 copper was selected for the augmenting rails and end-turn connections to decrease the overall gun resistance and to increase the reliability of the bolted joints. A pre-preg B-stage S-glass insulation tape was chosen as the rail-to-rail insulation material. Half-hard 301 stainless steel, 0.050 in. thick, was chosen for the lamination material because of its high yield strength (110 ksi) and availability in several stock thicknesses. The sidewall material chosen was UC-32 polyurethane.* This material is a stronger version of the material which was validated in the test gun. The rail and lamination package is installed inside an S-glass composite preload tube. The tube is used to place the laminations in compression and to provide bending stiffness of the entire structure for general handling purposes.

Structural Analysis

Structural analysis of the railgun was performed using ABAQUSTM run on the University of Texas Center for High Performance Computing (UTCHPC) Cray XMP-24. Loading information used in the FEM was obtained from LCODE results from which the primary and augmenting rail magnetic pressure distributions were obtained. As can be seen in the von Mises contour stress plot seen in figure 2, the maximum stress occurs at the lower corner of the molybdenum primary rail. This is a compressive stress caused by the large magnetic pressure occurring at that location; however, it does not exceed the yield stress for the molybdenum material.

* Conap Inc., Olean, NY

MISES (kpsi)

	VALUE
1	+7.00E-03
2	+7.00E+03
3	+1.40E+04
4	+2.10E+04
5	+2.80E+04
6	+3.50E+04
7	+4.20E+04
8	+4.90E+04
9	+5.00E+04
10	+6.30E+04
11	+7.00E+04

4101.0257

Figure 2. von Mises stress distribution at 400 kA peak current

Breech and Muzzle End-Turn Design

The breech was designed with the intention of minimizing the axial length requirement. (This greatly reduces the energy requirements of the autoloader). As seen in figure 3, it features a laminated design of G-10 insulation material with a complex array of electrical connections enclosed inside. The entire assembly is sandwiched between two heat-treated 17-4 PH stainless steel plates. Forty high-strength 1/4-20 UNC cap screws clamp the electrical connections and augmenting end turn connections with a minimum of 10,500 psi of compression. Phenolic tubes fit over each cap screw to prevent arcing between conductors.

s4101.318

4101.0258

Figure 3. Laminated gun breech assembled

The muzzle end-turn design utilizes two copper pieces which clamp the two augmenting conductors to the primary rails. Steel inserts are added to help maintain a constant modulus of elasticity in the transition from the gun barrel area to the muzzle area. The entire gun assembly can be seen in figure 4.

s4101.329

4101.0259

Figure 4. Small caliber gun assembled

Preliminary Determination of L'

After assembly, the gun was placed on a nonconducting surface and the inductance gradient was checked at several frequencies using an (LCR) video bridge. At 150 kHz the inductance gradient was measured as 1.32 $\mu\text{H}/\text{m}$. This inductance gradient compares well with that of the high frequency approximation of LCODE. The inductance is plotted as a function of distance down the bore in figure 5.

4101.0260

Figure 5. Gun inductance as a function of position down the gun bore

Test Results

The prototype railgun was tested at CEM-UT on the 1 MJ capacitor bank system. This system uses 10 capacitor banks providing approximately 60 kJ each to which an additional 4 capacitor banks of 100 kJ each were added. When staged properly, this energy storage system can roughly simulate the idealized small caliber compulsator waveform, although the pulse shaping inductors on the banks give a substantially higher di/dt than will the compulsator. Simulations were run modeling the capacitor bank firing times for various energy levels and launch masses. An explosive crowbar switch was added at the breech to decrease an anticipated muzzle arc problem which is inherent in the slow decay time of the capacitor power supply.

The original test plan called for increasing energy shots utilizing 32 g aluminum slugs as shown in figure 6. A contract addendum allowed for the integration of tungsten tipped, mass-stabilized, sabot projectiles which were designed by the Ballistic Research Laboratory (BRL). These projectiles (an updated design of the ones reported in [4] and figure 7), utilize the same aluminum armature geometry as the aluminum slugs, however a tungsten tip was added as well as a plastic sabot.

Two shots were performed with the 32 g aluminum slugs to check out the data acquisition system and to set the gun firing procedure. The next two

s4101.160

4101.0261

Figure 6. Aluminum armature slug

s4101.343

4101.0262

Figure 7. Tungsten tipped, mass-stabilized projectile

shots involved firing 39 g mass stabilized projectiles. A 30 ft flight range complete with yaw cards and a high speed framing camera was set up to better characterize the projectile aerodynamics.

The next four shots used a 48.5 g projectile package that featured a heavier tungsten nose section and an armature section which was elongated 60%. The energy was reduced for the first of these shots and brought up slowly due to the experimental nature of the test rounds. From figure 8, the highest muzzle energy

Shot #	Acc (kgees)	Mass (kg)	Vel (m/s)	Ip (kA)	Action (MA ² -s)	K.E. (kJ)	Comment
1	49.6	0.0291	275	152	27	1.10	checkout shot
2	75.0	0.0297	727	190	36	7.82	checkout shot
3	44.0	0.0391	508	167	32	5.04	projectile
4	105.0	0.0386	812	256	59	12.72	projectile
5	37.0	0.0485	250	170	25	1.51	proj./1.6 cal leg
6	56.0	0.0485	530	210	33	6.82	proj./1.6 cal leg
7	90.0	0.0480	715	264	65	12.39	proj./1.6 cal leg
8	n/a	0.0480	n/a	320	62	n/a	gun rails broke / proj destroyed

4101.0263

Figure 8. Summary of small caliber gun shots to date

reached at the time of this paper is 12.7 kJ. The inductance gradient for each shot was calculated on a dynamic basis from the in-bore velocity and action and was 1.25 $\mu\text{H/m}$. The wear of the molybdenum rails during the first shots was negligible; less than 3 mils was honed out of the bore in seven shots.

On shot 8 the primary rails were cracked and a localized area of the bore was destroyed. Peak current reached 320 kA during the shot and one of the primary rails experienced two similar looking cracks within 0.15 m of where the projectile was initially loaded. The damage was extremely localized; the gun structure remained intact and even the insulation between the primary and augmenting rails at the fractures was not damaged. Although the exact cause for the gun destruction is difficult to pinpoint, several theories prevail;

- 1) The sabot failed causing excessive rail bending and/or bore expansion (this is the primary suspect for the cause of the failure). The sabot has since been analyzed and a design modification has been indicated.
- 2) The stresses induced by the magnetic pressure coupled with the bending stresses induced in the transition region near the armature caused a failure. An elaborate three dimensional (3-D) finite element model was developed and results indicate that the stress rise due to the bending effects was negligible.
- 3) The molybdenum was flawed. Several small cracks were found in the molybdenum close to the bore area. The molybdenum used in subsequent guns will be inspected closely. Also examined in the finite element code was the possibility of using a high strength copper alloy for the primary rails. Results indicate that this may be possible, although the wear rate of such material is quite substantial compared to the molybdenum rails [2].
- 4) The insulation between conductors or conductors and laminations failed. The insulation methods used in the gun fabrication

process will be reviewed and improved where warranted; however, there is no substantial evidence of any insulation breakdowns in the gun.

Future Efforts

Pending complete results from the 3-D structural finite element analysis, a new gun will be produced and testing continued on the mass stabilized projectiles. Enough materials are being purchased for the construction of two guns including one built with dispersion strengthened copper rails. To continue the mass stabilized projectile integration into the small caliber gun, it has been recommended that the gun be tested using the CEM-UT iron core compulsator power supply. Details and further references for this power supply are presented in these proceedings [5]. This will lower the current rise time, which will in turn lower the acceleration and jerk that the sabot and projectile undergo during a railgun shot. The iron core compulsator will be used to continue testing of the small caliber railgun until the small-caliber compulsator is completed. Testing is scheduled to continue on the iron-core compulsator by mid February 1990.

Conclusion

Despite the temporary setback of the failed primary rails, the small caliber laminated and augmented launcher design represents an advance in the current state of the art in solid armature EM guns. Design constraints combined with high energy and current densities have resulted in several novel engineering concepts to be developed for the launcher. Materials for a new launcher have been ordered and fabrication should be completed by the end of December 1989. Current plans are to test the new launcher using the CEM-UT iron-core compulsator power supply starting in late February 1990.

Acknowledgment

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