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LARGE-BORE RAILGUNS

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Design and Testing of Solid Armatures for Large-Bore Railguns

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Abstract: A solid metal railgun armature called the "Fishbone" has been designed and tested at significant velocity, in both square and round bore configurations. The name "Fishbone" describes a structure consisting of multiple, independent, compliant contacts. Primary measures of success are low muzzle voltage and post-shot bore integrity. Experiments resulting in armature velocity in excess of 1.9 km/s have resulted in smooth muzzle voltage traces with peak values of 50 to 100 V and negligible bore damage.

Design and performance issues important to the successful launch of a solid armature and the features of the Fishbone that address those issues are discussed. Those issues include contact maintenance and gun stiffness, armature compliance, wear, thermal and structural integrity, and materials selection.

Shot data included are current, velocity, muzzle voltage, and post-mortem physical analysis.

Introduction

The development of the railgun is being pursued by several private, university and government organizations in the U.S. and elsewhere. The aim of many of these organizations is to develop railguns for military purposes, including tactical weaponry. Tactical applications of railguns require a lightweight system that performs dependably. Two disadvantages to rail accelerators, up to this point, have been low efficiency, dictating the need for heavy, voluminous power supplies, and inordinate rail damage, necessitating bore refurbishment following each firing.

Although the armature that carries the gun current and pushes the projectile down the bore of the gun is one of the smallest components in a railgun system, improvements in armature performance and efficiency can dramatically reduce the overall size of the system and its power requirements. Most previous railguns have been fired with arc armatures. The arc that drives the projectile in this type of accelerator produces a large voltage drop resulting in a significant energy loss. The loss severely lowers the efficiency of the entire system, especially at relatively low velocities. Sadedin showed that the ratio of energy dissipated in the arc to the kinetic energy in the projectile is proportional to four times the arc voltage and inversely proportional to the projectile velocity. He cites as a typical example where 200 to 300 V arc drops for 200 to 500 kA drive currents dissipate millions of watts of power in a constant current railgun [1]. As a result, larger power supplies and power conditioning components are required to produce the desired projectile velocities. Sadedin's results are supported by Barber, who concluded that solid armatures exhibit higher electromechanical conversion efficiency below the "crossover velocity" of 10 km/s (33,000 ft/s) [2].

Additionally, the high temperatures and high pressure gasses associated with an arc in a railgun can cause extensive damage to the bore [3]. Often, the damage is such that the bore must be re-worked prior to firing again. At the very least, most arc

drive experiments are followed by a thorough bore cleaning and honing. In addition to the bore damage, the residue left behind by an arc can result in secondary current paths that further lower conversion efficiency [4].

One way to address these issues is to use a solid armature as the projectile driver. It should be noted that the label "solid" is something of a misnomer, since it is doubtful that the armature material contacting the rails remains in a solid state as the armature travels along the rails under Lorentz acceleration. The interface at the rail surface is subject to the passage of large currents and the resulting joule heating. In addition, frictional effects at high velocity also cause heating and wear. For the purposes of this paper, "solid" armatures refer to those armatures that exhibit behavior more closely resembling solid, galvanic sliding contacts than armatures exhibiting behavior typical of arc contact. In the context of railgun armatures, that behavior is manifest as low muzzle voltage (less than 100 V, peak) and the absence of severe bore damage.

Previous work at the U. S. Army Armament Research, Development and Engineering Center demonstrated the utility of copper filament armatures in large-bore railguns. The results showed minimal bore damage at velocities around 1 km/s (3,300 ft/s). More important, the work explored and identified the design issues relevant to the successful design of a solid armature at higher velocity. These issues included the importance of multiple contact points; maintenance of solid armature material near the rail-armature interface so that contact is maintained as the projectile travels over asperities, as the bore deflects, and the armature wears; the importance of armature stability to the maintenance of contact; and the thermal and structural integrity of the armature [5].

Another encouraging result was reported by Barber, who claimed successful launch of a solid armature at 1.7 km/s (5,600 ft/s) [6].

In addition to the issues raised above, another important design issue is the parasitic effect of the mass of the armature on the net efficiency of conversion of kinetic energy to a useful payload. The minimum mass of the armature is limited by joule heating, as characterized in terms of the electrical action and action constant of the armature mass [7]. For a given muzzle energy, minimizing the mass of the armature effectively results in more kinetic energy being transferred to the payload.

The contact assured, or "Fishbone," armature design developed at the Center for Electromechanics has allowed for experimental investigation and trade-off studies of the above issues. The resulting design ensures contact, structural and thermal integrity, and attempts to minimize the mass of the armature. This paper includes the results of Fishbone armature testing to this point in time. The details of the design of the Fishbone armature will be presented elsewhere.

13 mm Square Bore Experiments

Initial experiments were performed using armatures that were designed to be fired from a barrel that was built for use in the GEDI project. The accelerator was 1 m (40 in.) long and had a 13 mm (0.5 in.) square bore. The rails were dispersion strengthened or ETP copper and the sidewalls were polycarbonate. The containment structure was a four-piece clamshell made from steel [8].

The Fishbone armature, shown in Figure 1, was made from 7050 T73654 aluminum and titanium stabilizers. The armature body was fabricated by electro-discharge machining. In latter shots, the contact surfaces were finished on a surface grinder. A 0.25 to 0.30 mm (0.010 to 0.012 in.) interference fit between the armature and the rails provided for initial contact force and allowed contact to be maintained as the bore grew or the leaves passed over an asperity. Zero-interference bore riders were attached to the fore and aft tabs to provide stability to the projectile. In early experiments, the bore riders were Nylon, but several failures were attributed in part to bore rider failure. The Nylon did not provide enough resistance to lateral deflection. In addition, every Nylon bore rider failed in shear. Consequently, a stiffer material was chosen. Titanium bore riders provided the required strength and stiffness and their relatively high resistivity (along with the fact that the titanium-rail contact pressure was negligible) prevented them from carrying current. A series of six experiments were performed using 13 mm square armatures and data was successfully collected from five of those experiments. Included here are the results from three experiments that are considered to be representative. A summary of the results of all of the reported experiments is shown in Table 1.

Figure 1. Fishbone armature assembly with titanium bore riders.

In shot #7, the total projectile mass was 15.9 g and the peak current in the accelerator was 290 kA. The exit velocity, determined from position vs. time data extracted from traces from B-dot probes, was 635 m/s (2,080 ft/s). The peak muzzle voltage was 10 V. The electrical data from the shot is shown in Figure 2.

Examination of the muzzle voltage trace shows high variation for the first milli-second of acceleration. The shape of this variation corresponds almost exactly to the variation of the breech voltage trace and is attributed to the turn-on points of the capacitor power supply modules. Once all of the modules were switched on, the muzzle voltage trace smoothed out, with the peak-to-peak muzzle voltage remaining under 4 V. This variation is attributed to commutation events as the contacts wore or encountered asperities on the rail surface.

The smooth shape of the field probe traces suggests that a uniform sheet current traveled the length of the accelerator. The variation in the first probe signal is due to the field variation as the power supply is switched on.

Table 1. Summary of experimental data

Shot Parameters	13-mm 1 m Long Square-Bore			45-mm 3 m Long Round-Bore			32-mm 3 m Long Round-Bore	
Shot/Run No.	7	10	11	2	3	4	85	87
Accelerated Mass [g]	15.9	19.0	18.9	365	365	1,445	67.2	65.4
Insertion Force [kN]	N/A	8.1	4.9	85.7	37.6	37.1	N/A	14.5
Interference [mm]	0.305	0.356	0.356	0.508	0.508	.0508	0.038	0.118
Velocity [m/s]	635	700	N/A	1,250	1,300	~600	755	1,889
Peak Current [MA]	0.290	0.300	0.335	0.98	1.13	1.29	0.512	0.555
Muzzle Current [MA]	0.090	0.060	0.120	0.57	0.40	N/A	-0.046	-0.211
Muzzle Volts (Peak) [V]	10	7	130	40	45	720	394	79
Contact Area (average*) [cm ²]	2.9	2.9	2.9	27	22	22	8.1	8.1
Current Density (average*) [kA/cm ²]	100	103	N/A	44	51	N/A	N/A	67
Peak Injector Current [MA]							-0.098	-0.151
Injector Muzzle Current [MA]							-0.013	-0.049
Injector Length [m]							0.098	0.152

* Contact area calculations based on total axial and circumferential contact length of the armature with the bore including spaces between contacts. Total current could easily be 3 to 8 times that listed in this table.

Figure 2. 13-mm Square-Bore; Shot #7 electrical data, showing gun current, muzzle voltage and B-dot signals.

Examination of the fired armature (Figure 3) shows that most of the leaf wear occurred on the rear-most leaf. Consideration of the velocity skin effect on the current distribution in the armature (Figure 4) shows that the current is concentrated in the rear of the armature [9]. The heating associated with the high concentration of current in the rear-most affects the properties of the aluminum, making these leaves more susceptible to wear. In addition, some of the damage to these leaves was probably caused by arcing. Damage along the length of the armature suggested that current was carried along a substantial length of the armature. It should be noted, however, that the damage is not symmetrical. On one side of the armature, the damage is obvious for the whole length; on the other side, damage is obvious only for the first six-tenths of length. The asymmetry may be due to some event occurring at muzzle exit or due to the lifting of the leaves off of the rail due to bore rider failure or balloting.

An optical comparator was used to examine the shape of the leaf tips before and after firing (Figure 5). The rail contact surface of this armature was not ground prior to firing. The sketch shows the

Figure 3. Recovered 13-mm armature after shot #7. The Nylon stabilizers were sheared off.

Figure 4. Plot of current distribution in 13-mm Fishbone calculated with 2-D electromagnetic finite-element analysis.

Figure 5. Optical comparison of 13-mm armature leaves before and after firing.

near symmetry of the wear on either rail contact surface. The rear-most leaf wore a maximum of 0.23 mm (0.009 in.) and the front-most leaf wore a maximum of 0.09 mm (0.004 in.).

The bore of the railgun was free of debris and soot and showed only slight traces resulting from the sliding electrical contact. Measurements made with an air gauge showed rail wear to be less than 0.08 mm (0.003 in.).

The results of shot #10 were very similar to shot #7. However, for this shot, the peak current was increased and the pulse width shortened. The exit velocity was 700 m/s (2,300 ft/s) and the peak muzzle voltage was 7 V. The electrical data (Figure 6) is nearly identical to the data of shot 7. Examination of the fired armature (Figure 7) shows severe melting and wear of the rear-most leaves, while the leading leaves show only wear due to friction and do not appear to have carried current. This result agrees well with the expectation that at higher velocity, the current is more concentrated at the rear of the armature.

Figure 6. 13-mm Square-Bore; Shot #11 electrical data, showing gun current, muzzle voltage and B-dot signals.

Figure 7. Recovered 13-mm armature after shot #10 with intact titanium stabilizers.

In shot #11, the total amount of energy stored in the power supply was increased in an attempt to increase the peak current, pulse width, and exit velocity. The peak current was 335 kA. As a result, the projectile came apart in the bore, causing the muzzle voltage to rise to 130 V. The electrical data from shot #11 is shown in Figure 8 and the recovered pieces of the projectile in Figure 9.

Examination of the bore showed deep gouging beginning approximately 150 mm (6.0 in.) from the initial position of the armature. The damage coincided with the muzzle voltage variation beginning after 1 ms. The peak current occurred at 0.99 ms, after the last capacitor module had fired.

Figure 8. 13-mm Square-Bore; Shot #10 electrical data, showing gun current, muzzle voltage and B-dot signals.

Figure 9. Pieces of 13-mm armature recovered after shot #11.

On another shot with similar armature failure and subsequent bore damage, a deposit of aluminum and a gold-colored aluminum/copper alloy was observed on the rail surface.

An initial assumption in the design of the original "Fishbone" armature was that current was distributed, to some degree, through multiple current-carrying fins. However, calculations assuming that all of the current was concentrated in the first (rear-most) fin suggested that the resultant electromagnetic load would be sufficient to shear off the fin at its base. Since all the fins had the same base cross section, and assuming the majority of the current was carried in the first, a shear-related failure would force current to commutate to the next fin, shearing it, and the next, and so on until all fins were sheared off. Then, the armature voltage would rise as an arc was formed in the absence of an effective galvanic contact.

This scenario is consistent with data and debris collected from shots where failure of the armature occurred. Observation of the remainder of a failed armature (Figure 9) shows that the fins on one side of the armature were sheared off. A curvature, characteristic of most failures, of the body of the armature, was probably due to plasma generated by the failure; being briefly confined between the fore and aft bore-riders, the plasma pressure would crush the fins on the in-tact side of the armature into the rails.

An alternate failure mechanism may be associated with the fact that the armatures were fired in a relatively "soft" railgun; under significant electromagnetic loads, the deflection of the rails may be greater than the interference of the fins with the surface of the rails. Loss of contact would cause arcing resulting in a runaway failure of the armature.

45-mm Round-Bore Shots

During the period that the 13-mm Square-Bore shots were being made, an ultra-stiff, 45 mm (1.75 in.) diameter bore diameter, 3 m long railgun was being designed and fabricated for the Task B railgun project. A new, unconventional gun design was to use a hydraulically-prestressed cylindrical ceramic rail-support structure to provide an effective gun stiffness between five to ten times that of existing gun designs. The underlying reasoning for fabricating such a stiff structure was to minimize rail surface deflections a solid armature would have to follow [10]. Under a peak load imparted to the structure from a 1.6 MA gun current, the maximum dynamic rail-to-rail deflection was calculated to be 0.23 mm (0.009 in.) using a transient finite-element analysis of the gun cross section.

Shortly before the new gun was installed and readied for testing, another iteration was made on the basic Fishbone design. A redesign was required to make the transition from round to square bores and to attempt to increase the performance capabilities of the armature concept. Given the results of the 13 mm gun shots and the observation that the failures may have been shear-related, the armatures were designed assuming that all the magnetic loading was in the first fin and could be transmitted through its base in shear. Fore and aft bore-riders were retained for in-bore stabilization, although no high resistivity or insulating surfaces were used. The number of fins were reduced from 15 to 6, in shot 1, and the design was based on 1.0 MA peak current. Shots 2 through 4 had only 5 fins (Figure 10).

Figure 10. 13-mm (0.5 in.) thick witness plate from 45-mm Round-Bore Shot 3 and sectioned armature (typical).

The material used in the first shot was the same as in the 13 mm shots, 7050 T73654 aluminum that had a yield strength of 446 MPa (65 ksi). Shots 2 through 4 used 7075 T651 aluminum with a yield strength of 503 MPa (73 ksi). In all shots, the rail material was a fully annealed OFHC copper alloy. The sidewalls were constructed from segments cut from a filament-wound tube fabricated of fiberglass in a polyester resin matrix.

In all, four experiments have been performed with the present 45 mm armature design. The first three were quite successful while the fourth experienced failure early in the shot. Muzzle voltage, gun current, and armature position-sensing probe (B-dot) signals are shown in Figures 11 through 13 with characteristic performance data points listed in Table 1.

Figure 11. 45-mm Round-Bore Shot 2; electrical data.

Figure 12. 45-mm Round-Bore Shot 2; expanded B-dot signals.

Figure 13. 45-mm Round-Bore Shot 3; electrical data.

One can see for shots 2 and 3, that the muzzle voltage traces remain below 8 V until the armature is half-way down the length of the bore. The first B-dot is located 1.5 m (59 in.) from the loading position of the armature with the others are located at 0.5 m (19.7 in.) intervals afterwards. At 1.5 m, the voltage traces begin to become somewhat erratic, at a velocity of about 900 to 1100 m/s (2,900 to 3,600 ft/s). At higher velocities, the voltage begins to spike to about 20 V and climbs to between 35 and 45 V at exit. The roughly triangular-shaped periodicity in the voltage spikes from 1.5 to 3.0 m in the gun suggest an ongoing commutation process or represent the voltage generated when current carrying spots in the armature bounce from high-spot to high-spot on the rail surface.

As seen from the photograph (Figure 14) and B-dot traces, the armature is quite intact and has conducted all the current in the gun. Upon expanding the data from the B-dot signals, as in Figure 12, one is able to discern irregularities in the signals as compared to that expected from a probe sensing an ideal sheet current. These irregularities may be indications of current being carried by at least two fins in the armature. This result is plausible given that the distance between contact points on any two fins is over ten times the diameter of the B-dot coil and the coil is located about 10 mm (0.4 in.) from the bore of the gun.

Figure 14. 45-mm Round-Bore Shot 3; armature in flight after muzzle exit.

After each shot, the bore was examined to determine if any damage occurred from the shot. In all shots, a thin layer of dark brown/black soot was deposited in the bore from breech to muzzle. After cleaning the bore surface with a white cloth and acetone, one could see slight pitting at the breech at the axial position the armature was loaded. Past that location, only a slight deposit of aluminum was noted, less than 0.025 mm (0.001 in.) thick, probably due to the armature contacts wiping the rails at a high contact force. Other than that, the copper rails and fiberglass sidewalls were in pre-fired condition.

Between shots, the bore was honed to consistent dimensions down the length. Although the bore was slightly egg-shaped, the rail-to-rail and sidewall-to-sidewall dimensions varied no greater than ± 0.019 mm (0.0008 in.). In the honing operation, approximately 0.05 mm (0.002 in.) of material was removed from the bore diameter. After honing, no evidence of prior shots was noted.

In contrast to the first three experiments, data plots from shot 4 (Figure 15) show that the armature was in distress early into the shot. The muzzle-voltage trace indicates that the armature maintained contact briefly, lost contact briefly, regained contact once again, and then failed to a plasma state. Although our goal was to duplicate the peak current carried by the armature in shot 3 (because more mass was to be accelerated), 1.29 MA was delivered to the gun due to modifications to the main circuit between shots. As a result, 30% more load was applied to the armature than in the previous shot. Because failure was indicated early in the shot, it is unlikely that the current had time to diffuse forward into other fins, or that contact was lost due to velocity effects,

Figure 15. 45-mm Round-Bore Shot 4; electrical data.

nor that the armature failed due to resistive heating. Given that the armature was designed to operate at 1.0 MA, worked successfully at 1.13 MA, and failed at 1.29 MA, the evidence at hand weighs in favor of a mechanical shear failure.

32-mm Round Bore Shots

Another ongoing project at CEM-UT is the Rapid-Fire EM Gun System. As a part of this project, a parallel effort was pursued to develop useful solid armatures for railguns. The system consists of three railguns, each of which have an augmented railgun injector, all driven by a single compensated pulsed alternator (Compulsator) [11]. The development team was investigating solid armatures as a means to increase system efficiency and minimize bore damage. Resultant armature designs drew on experience from the 13-mm square-bore shots. Modifications to the design included a conventional method for fabricating the Fishbone design in a cylindrical geometry. Several design iterations that had multiple thin fins were fabricated but failed when fired. Electrical data from a failed armature shot are shown in Figure 16.

Figure 16. 32-mm Round-Bore Run 85; electrical data.

After the first Task-B shot indicated that designing for shear was an important design criterion, another iteration was made to the 32 mm (1.25 in.) design. It too had fins that were sized to take the full electromagnetic load. The redesigned armature was fired (Figures 17 and 18) at the highest velocity achieved by CEM-UT to date, 1,889 m/s (6,198 ft/s), in a bore that had experienced 3 prior shots, and had not been honed between shots.

Figure 17. 6-mm (0.38 in.) thick witness plate from 32-mm Round-Bore Run 87, armature and plate fragments and typical, intact armature.

Figure 18. 32-mm Round-Bore Run 87 electrical data.

Subsequent shots were fired with slightly differing design parameters and resulted in varying success. Attempts were made to improve armature compliance and reduce its insertion force by cutting the fins at a more shallow angle although test results have showed only reduced performance. After comparing data from 10 compulsator-driven gun shots, one major trend was identified that indicated the most successful shots had the least injector muzzle-exit current prior to the armature entering the main gun. This suggested that as the armature exits the injector, arcing from the muzzle current damages the armature contacts before they enter the main gun. Upon reaching the main rails, the contact area has been reduced from the arcing and further increases the duty on the remaining contact surfaces. Steps are being taken to minimize the current at injector exit and further tests are planned.

Conclusions

A great number of electromagnetic designs and analyses have been performed on solid armatures for railguns, but experience holds that the problems associated with designing successful solid armatures require as much, if not more, mechanical design and analysis. Many problems including mechanical response of contacts sliding over surfaces at hypervelocities, structural integrity of a body constructed of materials that change electrical and mechanical properties as a function of time, strain-rate dependency of armature materials, and friction and wear of armature contacts must be addressed and solutions optimized.

Test data to-date indicates that these armatures should be designed so that its first "fin" is capable of transmitting the full electromagnetic acceleration load in shear through its base to the mass it is accelerating, and that its fins should be compliant enough to track any bore deflections. Although multiple fins have been used in all armatures fired, mechanical and electromagnetic data indicate that only one or two may be required.

Also, the current-carrying portion of the armature must be rigidly attached to and stabilized by an external structure that centers the armature in-bore to prevent it from cocking. These stabilizers, or bore-riders as they have been called here, may be made integral to the armature structure and may be made of conducting material so long as they are fabricated with a slight clearance with the gun bore. This is important because in the future, armatures may be an integral component in a projectile package that consists of an aerodynamic projectile, metal sabot and armature/pusher plate. In other words, the constraints placed on sabot design for railguns may be fewer than originally thought.

Examination of the gun bores confirm that by using an effective solid armature, bore damage is negligible and tools are now being designed and fabricated to quantify values of wear. Although bore materials used in these experiments are certainly not well suited for multi-shot applications, the damage has been minimal and in the future serious work remains such as studying more durable bore materials, such as molybdenum rails and ceramic sidewalls.

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