ACTIVE CURRENT MANAGEMENT FOR FOUR-RAIL RAILGUNS

J. H. BENO
U. S. ARMY

AND

W. F. WELDON
THE UNIVERSITY OF TEXAS AT AUSTIN

Presented at the
5th Symposium on Electromagnetic
Launch Technology
Eglin AFB, Florida
April 2-5, 1990

Publication No. PR-113
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512) 471-4496

ACTIVE CURRENT MANAGEMENT FOR FOUR-RAIL RAILGUNS

J.H. Beno
U.S. Army

and

W.F. Weldon
Center for Electromechanics
The University of Texas at Austin
10100 Burnet Rd., Bldg. 133
Austin, TX 78758-4497

Abstract: A system of auxiliary conductors designed to reduce current density peaks in railgun rails for four-rail, round-bore railguns is described. The effects on rail current density and projectile force are discussed. Railgun cross-sectional designs are presented for round-bore, four-rail railguns which operate at lower peak current densities and develop greater projectile forces than conventional two-rail, round-bore railguns.

Introduction

Continued railgun development toward high-energy devices that launch useful projectiles and have a lifetime of hundreds to thousands of shots, requires progress in two related aspects of accelerator design: (1) rail containment structures must be made capable of withstanding greater rail repulsion forces, without causing accelerators to become too bulky for their intended use; and (2) rails must sustain minimal heat-related damage during projectile launch. These issues are related because they primarily represent direct effects of railgun current and its distribution.

Methods to passively influence rail current distribution through proper rail cross-sectional design for railguns with multiple rail-pairs, have been previously explored.[1] Using multiple rail-pairs is beneficial in positioning currents and rail-repulsive forces in a few, evenly-spaced, radial directions for easier rail containment. It was determined that square- or round-bore accelerators with more than two rails suffer substantially aggravated proximity effects between neighboring rails. This necessitates either accepting higher peak current densities on rail corners--and increased thermal damage--to maintain the same projectile force; or 30 to 40% reductions in force for the same peak current density.

Methods to actively influence rail current distribution, using auxiliary current carrying conductors for two-rail railguns, have also been previously described.[2] Although the auxiliary conductors provide the added benefit of railgun augmentation, it was determined that conventional designs for two-rail, round-bore, augmented railguns are not satisfactory. Conventional augmented designs achieve greater projectile force than nonaugmented railguns for the same total railgun current, but local rail peak current densities are greater -- indicating probable increased rail thermal damage. A new augmenting rail cross-sectional design, which wraps around rail exterior surfaces, was developed to influence

and manage rail current distribution. Calculations show that two-rail, square- and round-bore accelerators employing properly designed wrap-around, augmenting conductors (designated henceforth as current guard plates) achieve significant improvements in rail current distribution. Round-bore accelerator designs with guard plates produce four to eight times the force produced by the conventional augmented, two-rail accelerator design, without increasing local peak current densities.

This paper presents results of research seeking to apply active current management concepts to multiple rail accelerators. Optimized designs, current distributions, performance parameters, and design implementation considerations are presented for four-rail, round-bore accelerators which use wrap-around guard plates for active current management and augmentation. These accelerators produce 2 to 3.5 times as much projectile force as simple, two-rail railguns operating with the same local peak current density limits.

Methodology

This paper represents a continuation of previously referenced research concerning multi-rail railguns and active current shaping of rail current distribution. The objective of the research reported here was to use optimization techniques to develop viable accelerator designs having both the widespread utility of round-bore railguns and the desirable distribution of outward rail forces which is inherent with multi-rail railguns. To facilitate comparisons, the guiding tenets of this optimization study are identical with those presented in the previously referenced papers. Furthermore, this paper concerns active shaping of rail current, so passive current-shaping measures were not applied to railgun rails. Therefore, the only rail cross-sectional shapes considered were 1.0 cm thick, circular segments, shown in figure 1, with sharp rail-corners (corner radii = 0.1 cm).

Previously reported results concerning simple, multi-rail railguns [1] and results concerning two-rail railguns with guard plates for active rail current shaping [2] allowed the following features to be incorporated into this study of multi-rail railguns with guard plates:

- (1) The computational and optimization techniques developed in the previous papers were used without change.

Figure 1. Round-bore railgun geometry. Cross-section of a two-rail, round-bore railgun is shown, defining the arc length along the perimeter (s), the rail thickness (t), the bore radius (r_b), and the angle subtended by the half-rail (α). Although not shown, the rail corners are rounded with a radius of 0.1 cm. The dotted line encloses the railgun bore

Figure 2. Round-bore railgun with addition of wrap-around guard plates. Only the right rail and guard plate are shown. The drawing defines the radius of the top inside rail corner, r_t ; the radius of the top portion of the guard plate, r_p ; the thickness of the portion of the guard plate above and below the rail, t_t ; and the rail and guard plate vector potentials, A_r and A_g . Vector potentials are shown as into the page; currents are also directed into the page. The rail variables are the same as defined in figure 1

- (2) Only four-rail railguns with guard plates were considered. This simplification was appropriate because previous results indicated that four-rail railguns experience less aggravated proximity effects than six- or eight-rail railguns, which leads to a greater force-producing capability for the same imposed local peak current density limits.
- (3) Only wrap-around guard plates, such as shown in figure 2, were considered because previous two-rail results indicated that the wrap-around design is most effective for influencing rail-current distribution.

The optimization variables and procedures discussed previously [2] for wrap-around guard plates were used without change. To summarize these procedures, the variables available for optimization involve guard plate cross-sectional shape, rail total current, and guard plate total current. This assumes independently-powered rails and guard plates, which will be discussed in a later section. The set of geometric variables for optimization were determined after several calculations to investigate relative effects on rail and guard-plate current distributions. To simplify optimization procedures, this total set of variables was kept as small as possible. The variables selected (shown in figure 2) were the radius of curvature on the guard-plate top inside corner, r_t ; the radius of the top portion of guard plate, r_p ; the angle subtended by the rail, α ; and the relative magnitude of specified magnetic vector potentials for the rail and guard plates (which affects the total currents in each). All other geometric variables were fixed at appropriate values as follows:

- (1) The other guard-plate corner radii were set large enough to insure that local current density peaks were not severe, while rail corner radii were set at 1 mm, the same used for the railgun associated with figure 1.

- (2) The separation between guard plates and rails was set at 2 mm to allow for insulation.
- (3) The difference between the angle subtended by rails (α , in figure 1) and that subtended by the guard plate was fixed at approximately 20° , so that varying rail angles also varied guard plate angles by the same amount. This fixes the thickness of the portion of guard plate above and below the rail (t_t in figure 2) at 0.75 cm. While it has been found to be beneficial to reduce this dimension as much as possible, less than 0.75 cm would lead to excessive heating in this portion of guard plates.
- (4) The rail and guard plate thicknesses were fixed at 1.0 cm.
- (5) The bore radius was set at 2.257 cm, which creates a 16 sq. cm bore.

This study only addressed accelerator force-producing capabilities, isolated from power supply considerations. It has been assumed that power supplies exist which can drive each conductor with any total current desired. Therefore, projectile force was used to quantify "goodness" during accelerator optimization. Rail and guard plate current densities were calculated in the same manner as in previously referenced work. Projectile force was computed after scaling current distributions to impose specified local

peak current density limits for the rails and guard plates. This requires that both rail and guard plate distributions be scaled by identical factors when performing a force calculation.

For the purposes of this paper, all force calculations are made with local rail current density peaks limited to a specified peak value, arbitrarily set at 1 MA/in. This approach is an attempt to compare performance of different accelerators under conditions of approximately equal accelerator damage. Since guard plates act in an augmenting role and do not suffer effects of sliding contact friction with armatures or armature contact voltage drop, they can thermally sustain higher peak current densities than rails. It is not known how much increased peak current guard plates can carry, relative to rails. However, simplified thermal analysis indicate that guard plates can have peak current densities which are 1 to 3 times greater than rails for equivalent thermal damage.[2] To cover this range from 1 to 3, projectile force was maximized with guard plate peak current densities successively limited to 1.0, 1.5, 2.0, and 3.0 MA/in. As will become evident, for the comparative studies of this paper, actual numerical values assigned to rail and guard plate peak current density limits are not important. Relative magnitudes of current density limits assigned to rail and nonrail conductors are important. It is also imperative that density limitations be applied consistently for all comparisons.

Baseline Performance

As a basis of comparison for the remainder of this paper, results for a simple two-rail, round-bore railgun are presented in figures 1 and 3. The two figures are related and should be considered together. Figure 1 defines the general round-bore railgun and its various parameters. Normalized current density for the top half of the right rail of a particular round-bore gun is presented in figure 3. The current density of each half-rail has an identical distribution. The plot is normalized so that the magnitude of current density on the center of the back of the rail is one. The position scale in figure 3 refers to arc length, s (in cm), in figure 1. Position, therefore, has its origin at the center of the front of the rail and proceeds around the rail perimeter, ending at the center of the back of the rail. Axis labels and normalization procedures for all current density plots in this paper are similar to those of figure 3. Note that current density on the inside rail corner ($s \approx 1.75$) is approximately four times that on the center of the front of the rail. Another strong peak exists on the outside corner ($s \approx 2.75$). From the plot, it is apparent that the primary region of rail damage is in the vicinity of the inside corner ($s \approx 1.75$), since this region not only has the highest level of Joule heating, but is also in contact with the moving armature. As a result, additional heating occurs due to contact voltage drop and friction. A projectile force of 0.346 MN is calculated, based on a peak current density of 1.0 MA/in. assigned to the rail inside corner ($s \approx 1.75$) and the remainder of the current density scaled in accordance with figure 3. It is worth mentioning that round-bore, two-rail railguns with conventional augmentation have exacerbated rail current-density peaks compared to those of simple, round-bore railguns. Although plots are not provided, the peak on the rail inside corner ($s \approx 1.75$) is increased relative to the remaining rail current density. As a result, augmented, round-bore railguns, operating with the same rail peak current limitations, actually produce

Figure 3. Normalized current density for the two-rail, round-bore railgun of figure 1. For this plot, $r_b = 2.257$ cm (bore area = 16 sq. cm), $\alpha = 45^\circ$, $t = 1.0$ cm, and all corner radii = 0.1 cm. This railgun produces a projectile force of 0.346 MN with a current of 1.184 MA

smaller projectile forces than their non-augmented counterparts. More detailed descriptions of computational techniques, current distributions, and rail thermal damage estimates are contained in references [1,2]. The next section presents the results of optimization studies concerning four-rail railguns with augmenting guard plates.

Force-Optimized, Guard Plates for Round-Bore, Four-Rail Railguns

This section presents results of force optimizations. Figures 4 through 6 display results obtained for the case in which guard plate peak current density is 2.0 MA/in. (rail current density is 1.0 MA/in.). Note that this optimum design requires that guard plates overhang the rail, protruding into the bore. This design yields the largest force per unit of maximum peak rail current density. As discussed in a previous paper [2], the guard plate overhang feature is instrumental in reducing the major rail current density peak ($s \approx 1.75$ in figure 3). Nevertheless, recognizing that this overhang may cause difficulties in practical railgun fabrication and operation, similar optimizations were performed with the guard plate top radius (r_p in figure 2) equal to the bore radius. These results are displayed in figure 7 through 9. Again, guard plate peak current density is 2.0 MA/in. and rail current density is 1.0 MA/in. for these figures. Figures 4 through 7 both illustrate a significant limitation of multi-rail railguns with guard plates. Recall that the thickness of the portion of guard plate above and below the rail (t_t in figure 2) was fixed at 0.75 cm. As a result, a 16 square-centimeter, round-bore, four-rail railgun has approximately 150° of bore circumference occupied by guard plate material. This leaves a limited portion of the bore perimeter to be occupied by magnetic flux and

Figure 4. Scale drawing of a round-bore, four-rail railgun with guard plates optimized for maximum force. Referring to figure 2, $r_t = 0.650$ cm, $r_p = 2.057$ cm, and $\alpha = 9.93^\circ$. The guard plates overhang the rails and protrude into the bore 0.199 cm, i.e., bore radius minus r_p equals 0.199 cm.

Figure 6. Normalized guard plate current density for the railgun of figure 4. This plot is the companion plot of figure 5. Current densities are normalized by the same factor in figure 5 and figure 6

Figure 5. Normalized rail current density for the railgun with guard plates of figure 4. Force developed with this gun is 1.23 MN, with a total rail current of 1.86 MA and a total guard plate current of 6.29 MA. This calculation invokes limits of ≤ 1 MA and ≤ 2 MA for maximum allowable current density peaks in rails and guard plates, respectively

Figure 7. Scale drawing of a round-bore, four-rail railgun with guard plates optimized for maximum force. Referring to figure 2, $r_t = 0.642$ cm and $\alpha = 14.26^\circ$. For this optimization, r_p was fixed at the bore radius of 2.257 cm

Figure 8. Normalized rail current density for the railgun with guard plates of figure 7. Force developed with this gun is 1.06 MN, with a total rail current of 2.01 MA and a total guard plate current of 5.70 MA. This calculation invokes limits of ≤ 1 MA and ≤ 2 MA for maximum allowable current density peaks in rails and guard plates, respectively

Figure 9. Normalized guard plate current density for the railgun of figure 7. This plot is the companion plot of figure 8. Current densities are normalized by the same factor in figure 8 and figure 9

the four rails. Reducing t_t can alleviate this crowding problem, but also introduces thermal problems in the guard plates. This effect is less severe in larger bore railguns.

Results for force optimizations invoking the other guard plate current densities (1.0, 1.5, and 3.0 MA/in.) are presented in tabular form only. In Table 1, variable names at the top of each column refer to the variables depicted in figure 2. Values for rail and guard plate currents represent total railgun rail and guard plate currents, not the current flowing in each rail or guard plate. The current in one rail or guard plate is half the value displayed in the table. Table 1 is divided into two categories. The first category involves force optimizations which were accomplished with guard plate top radii (r_p in figure 2) fixed at the bore radius. For the second category, no restrictions were placed on r_p . Trends displayed in Table 1 are similar to those reported previously for two-rail force optimizations.[2]

Table 1. Force-Optimization Results (four-rail, round-bore)

Max Guard Density (MA/in.)	r_t (cm)	Overhang ($r_b - r_p$) (cm)	a_r (deg)	Force (MN)	Rail Current (MA)	Guard Current (MA)
1.0	0.650	0.000	8.76	0.736	1.738	2.498
1.5	0.650	0.000	12.04	0.947	1.891	4.205
2.0	0.642	0.000	14.26	1.059	2.008	5.695
3.0	0.629	0.000	16.63	1.158	2.135	8.422
1.5	0.650	0.131	8.95	0.999	1.746	4.489
2.0	0.650	0.199	9.93	1.232	1.864	6.290
n/a	n/a	n/a	45.00	0.346	1.184	n/a**

** Two-rail, round-bore railgun, without guard plates, for comparison.

Series-Wired Systems with One Power Supply

The previous results assumed independently powered rails and guard plates. The complexity of separate rail and guard plate power supplies can be easily avoided with only minor performance degradation. Segmenting the guard plate cross-section into a few, properly-proportioned "slices," wired correctly in series with each other and with the adjacent rails, can provide the high total currents required in the region of space occupied by guard plates, with a single power source. The number of guard plate sections must be the integer which most nearly equals the optimum ratio of guard plate current to rail current from table 1. Guard plate partitioning must be in accordance with the guard plate current distribution (such as displayed in figures 6 or 9) so that each section carries equal current and the combined distribution of all sections is still nearly identical to the current distribution of the single optimized guard plate design. Calculations for a two-rail example have shown that segmented guard plates result in a projectile force which is only slightly less than optimal. Furthermore, the two-rail example showed that a good approximation for effective inductance gradient of series-wired railguns with segmented guard plates, can be obtained using the optimized force and current values (contained in table 1). Using $F = .5Li^2$ and the values from table 1, this implies that four-rail railguns, with properly partitioned, segmented guard plates have effective inductance gradients of $0.5 \mu\text{H/m}$. This inductance gradient is very high for four-rail railguns, and allows the use of most existing railgun power supplies.

Conclusions

Several conclusions can be drawn from the results presented in this paper. The major conclusion is that using guard plates for active rail current shaping makes it possible to design viable accelerators which have the utility of round-bores and the desirable distribution of outward rail forces which is inherent with multi-rail railguns. Additionally, these accelerators can produce 2 to 3.5 times the force produced by simple round-bore, two-rail railguns or normal augmented, round-bore, two-rail railguns -- without increasing local peak current densities. The actual performance obtained, for a particular choice of relative rail and guard plate current densities, is primarily a function of the complexity of design. The more complex designs require guard plates to overhang rails slightly (protruding into the bore space, similar to rifling in a conventional gun barrel), and the use of separate power supplies for the rail and guard plate

conductors. These added complexities represent unacceptable complications for many applications, but may be justifiable for others. The requirement to build high energy accelerators which can withstand hundreds or thousand of shots in a military field environment may necessitate progressing toward more elaborate railguns, such as those presented in this paper.

References

- [1] J.H. Beno and W.F. Weldon, "An Investigation into the Potential for Multiple Rail Railguns," IEEE Transactions on Magnetism, vol 25, no. 1, January 1989, pp 92-96.
- [2] J.H. Beno and W.F. Weldon, "Railgun Current Guard Plates: Active Current Management and Augmentation," IEEE Transactions on Magnetism vol 17, no. 3, June 1989, pp 422-428.