Coilgun Structures

J. A. Andrews

The University of Texas at Austin
Center for Electromechanics
10100 Burnet Rd., Bldg. 133
Austin, TX 78712
(512) 471-4496

***ABSTRACT*—The structural design of a hypervelocity coilgun is influenced by a variety of complicated, and sometimes conflicting, technical issues. The basic launcher configuration and/or material selection is often dictated by requirements that are nonstructural in nature, and yet the mechanical loads developed in a coilgun are similar in magnitude to those in competitive railguns. These issues often become particularly important in the armature, because the desire to reach a high muzzle velocity with a fixed amount of stored energy usually implies that the armature mass be minimized.**

Research on coilguns at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) has yielded considerable insight into the optimal design of coilgun structures. This research has indicated that the structural requirements are strong functions of launcher classification as well as acceleration mode. As a result, CEM-UT has built and tested the DC coaxial accelerator (DCA) coilgun, which is a multistage pulsed induction launcher that makes extensive use of composite material technology.

This paper presents analytical techniques (closed-form and numerical) used to make structural design calculations in the DCA launcher. The evolution of the multiturn wound DCA armature design is discussed. In addition, measured plastic deformation of this armature after a high energy experiment is compared to that predicted by finite element analysis.

INTRODUCTION

To date, most research regarding the development of hypervelocity coilguns has been devoted to physics and system engineering issues. The primary focus has been the complex, dynamic interaction between a coilgun's power supply, barrel, and armature. As a result, a variety of flexible analytical models [1,2,3] have been developed that allow researchers to evaluate the relative merits of the seemingly infinite variety of coilgun configurations. In addition, these models have made it possible to accurately predict a wide variety of important system parameters for a given design, such as the adiabatic temperature rise in pulsed conductors, and the back EMF across barrel switches.

The work was supported by U.S. Army ARDEC under contract no. DAAA21-87-C-0247.

On the other hand, relatively few coilgun programs have had the funding and/or personnel to pursue large-scale laboratory experiments. Therefore, certain critical engineering issues such as lightweight structural design have not received as much attention. These issues are crucial if coilguns are to compete with railguns and other launchers for hypervelocity missions.

In the last decade, research on coilguns at CEM-UT has included programs devoted to detailed analytical studies as well as full-scale laboratory experiments. As a direct result of this research, engineers at CEM-UT have found that the structural requirements of coilguns depend on accelerator classification (synchronous, traveling wave, or pulsed induction) and acceleration mode (push or pull). Unfortunately, in many cases the material for a given gun component is dictated entirely by nonstructural properties such as conductivity (or lack thereof) and heat capacity.

In order to study the structural requirements of a generic coilgun, it is helpful to define the launcher classification and acceleration mode, both of which significantly impact the location and material selection for the support structure in the armature and barrel.

LAUNCHER CLASSIFICATION

Synchronous and Traveling Wave Accelerators

In general, these accelerators are capable of producing a smooth acceleration profile, which limits the dynamic effects (vibration) in the armature. The armature is subjected to a relatively constant load state, and it should be sufficient to design its support structure for the average acceleration load. Attention should be paid to any dynamic effects that occur at the breech (and muzzle, if the armature is to be reused).

This is not necessarily true for the barrel. In a synchronous launcher, such as an advancing or collapsing wave device, each barrel coil is subjected to two load states ("current on" and "current off"), with a relatively quick transition time in between. If this transition time is on the order of the barrel's fundamental period of vibration, a significant amount of dynamic stress amplification can occur.

0018-9464/93$03.00 © 1993 IEEE

A similar problem exists in traveling wave launchers, where each barrel coil is subjected to one or more (sinusoidal) pulses of current in the launch time frame.

Pulsed Induction Launchers

These accelerators often produce acceleration profiles with a large amount of ripple, which can cause a great deal of vibration in both the armature and barrel. However, if the armature is being influenced (driven) by multiple barrel coils, the acceleration profile tends to be smoother, and the armature stress problem approaches the constant load state common to synchronous and traveling-wave machines. Structural designs should be based on peak acceleration conditions, as determined by detailed performance simulations.

Accelerator Mode

Push

If the armature is being pushed down the bore of the gun, the J x B body forces manifest themselves such that the armature is compressed radially inward, while the barrel is expanded radially outward. Thus, structural support material can be placed inside the armature winding and outside the stator winding. This is a significant point, inasmuch as the air gap in such a machine can be small, which allows high electromagnetic coupling between the armature and stator coils. This leads to high energy conversion efficiencies.

Pull

If the armature is being pulled down the bore of the gun, the radial components of the J x B body forces are reversed from those in a push mode accelerator. Thus, the armature is expanded radially outward while the barrel is compressed radially inward. The logical location for structural support, which is outside the armature winding and inside the stator winding, can drastically increase the width of the air gap. Electromagnetic coupling, and hence energy conversion efficiency, suffers.

Stress Calculations

The nonuniform, dynamic nature of the J x B forces developed in typical coilgun windings make detailed electromagnetic and structural analyses invaluable. At the present time, the most prevalent technique for such analysis uses the finite element method (FEM), but other methods (finite difference, boundary element) might suffice in some circumstances. At CEM-UT, all coilgun designs are first analyzed with TEXMAP (an in-house electromagnetic FEM code) to determine the J x B forces in the system, and then these are used as loads in a model on ABAQUS (a commercially-available mechanical FEM code). Design modifications are then made in the windings and their structures based on this detailed analysis.

There are two extremes in design philosophy for coilgun structures. One is to make the windings themselves sufficiently strong to react the J x B loads without any external support structure. Experience has shown that, except for a few special cases, this is not practical for a hypervelocity launcher. (It could be argued that the solid metallic armature used in many pulsed induction launcher designs has no support structure, but in reality a great deal of the material in such an armature carries little or no current at any given instant, and should be considered structure rather than conductor). The other extreme case is to assume that the windings are so pliable that they simply transfer all the load to the support structure. This is obviously conservative, in that the structure will be overdesigned, but following detailed FEM analysis the designer can determine areas in which mass can be trimmed from the structure.

Each of these cases lends itself to a simple hoop stress calculation taken from thick-walled pressure vessel formulas tabulated in "Roark's Formulas for Stress & Strain" [4]. In most coilguns, hoop stress dominates the stress vector. To predict the stress state in a self-supporting winding that carries a uniform current, the equations in Roark Table 32, case 1f are appropriate. This case deals with a radial body force that varies linearly from the inner radius to zero at the outer radius. Note that this radial body force is the cross product of the uniform azimuthal current density J_θ with the axial flux density B_z, which drops linearly from the inner radius to zero at the outer radius. In reality, for a finite length coil, the field at the outer radius is small and opposite in sense to that at the inner radius, but the zero-field approximation is sufficient for design purposes. The maximum hoop stress occurs at the inner radius:

$$\sigma_\theta^{max} = \frac{\delta_b}{12\,(a-b)\left(a^2-b^2\right)}\left[2a^4+(1+\nu)a^2\left(5a^2-12ab+6b^2\right) -(1-\nu)b^3(4a-3b)\right] \quad @\ r=b$$

$$\delta_b = J_\theta \text{ x } B_z^{r=b}$$

where,

J_θ ≡ azimuthal current density
$B_z^{r=b}$ ≡ axial flux density at winding inner radius
a ≡ winding outer radius
b ≡ winding inner radius
ν ≡ Poisson's ratio

If the axial flux density is not known, it can be approximated with the following equation:

$$B_z^{r=b} \cong \mu_o \frac{Ni}{l}$$

where,

μ_o ≡ permeability of free space = $4\pi \times 10^{-7}$ H/m
N ≡ number of turns in winding
i ≡ current in winding
l ≡ axial length of winding

For a winding in which one wishes to incorporate an external support structure, the maximum hoop stress in the support occurs at its inner radius, and can be predicted with Roark Table 32, case 1a:

$$\sigma_\theta^{max} = p\frac{c^2 + a^2}{c^2 - a^2} \quad @ \quad r = a$$

$$p = \frac{\left(B_z^{r=b}\right)^2}{2\mu_o}$$

where,

$B_z^{r=b}$ ≡ axial flux density at winding inner radius
a ≡ winding outer radius (support structure inner radius)
b ≡ winding inner radius
c ≡ support structure outer radius

If an annular internal support structure is desired, the maximum hoop stress in the support again occurs at its inner radius, and is modeled with Roark Table 32, case 1c:

$$\sigma_\theta^{max} = \frac{-2pb^2}{b^2 - d^2} \quad @ \quad r = d$$

$$p = \frac{\left(B_z^{r=a}\right)^2}{2\mu_o}$$

where,

$B_z^{r=a}$ ≡ axial flux density at winding outer radius
a ≡ winding outer radius
b ≡ winding inner radius (support structure outer radius)
d ≡ support structure inner radius

Note that if the internal support structure is solid as opposed to annular, the maximum hoop stress in the support is equal to the pressure defined above, which is only half what one would expect by letting d = 0. The presence of an infinitesimally small central hole doubles the hoop stress in the solid cylinder.

Numerical Analysis

As discussed previously, numerical analysis on coilguns at CEM-UT utilizes an electromagnetic FEM code (TEXMAP) to determine J x B body forces for known coil currents, and a mechanical FEM code (ABAQUS) to determine the resulting stresses arising in the conductors and their associated support structures. Quite often the currents are calculated with one of several in-house current-filament codes, which couple lumped-element power supply, buss, and switch models to distributed filament coil models. These codes incorporate an adiabatic heating routine, and can model either wound coils (uniform current density) or solid coils, so that nonuniform current densities (hence nonuniform heating) are taken into account. The variation of conductor resistance and specific heat with temperature can be modeled if necessary.

Dynamic analysis is rarely, if ever, performed with TEXMAP, simply because it is much more cost-efficient to determine the electrical dynamics with a current-filament code. However, the mechanical dynamics (vibration) of the coilgun system are always determined with ABAQUS. If necessary, coupled mechanical/thermal analysis can be performed. The orthotropic nature of transposed conductors and hoop-wound coil support structures is also modeled, as ABAQUS is capable of analyzing fully anisotropic materials. The properties of these materials are determined either through composite material models [5] or through testing.

As a specific example of the complete structural design process, the following analysis pertains to the armature for the 45 mm DCA pulsed induction launcher [6,7,8]. This push mode launcher, shown in Fig. 1, was designed to accelerate a 0.225 kg armature to 2,000 m/s in 47 discrete stages. Each stage incorporates a 125 μF, 20 kV energy storage capacitor as a power supply, and is switched with ignitrons. CEM-UT fabricated the first five stages of this launcher, using 500 μF, 10 kV capacitors (causing a slight performance penalty when compared to the original design), and successfully accelerated a 0.250 kg armature to 300 m/s with the first four stages. (The fifth stage had an ignitron fail during full energy testing). Performance for this launcher was predicted quite accurately with the current-filament codes developed at CEM-UT.

Simulations showed a peak current of approximately 100 kA in the 17-turn stator coils, which were 7.85 cm long. The approximate peak axial flux density in the air gap was:

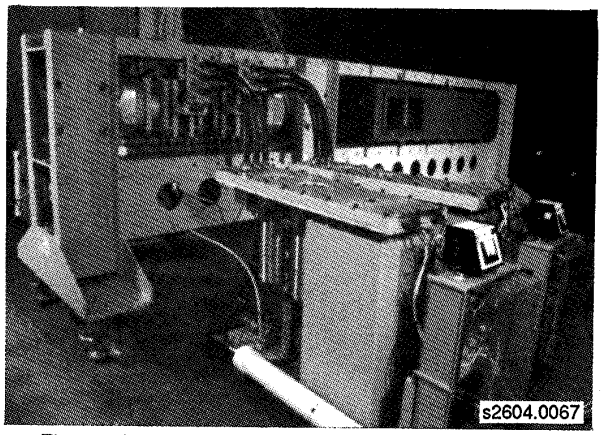

Fig. 1. 45 mm pulsed induction launcher, power supplies, and catch tank

$$B = \left(4\pi \times 10^{-7}\right)\frac{(17)(100,000)}{0.0785} = 27.2\ T$$

The corresponding magnetic pressure, which tends to crush the armature, was:

$$p = \frac{(27.2)^2}{8\pi \times 10^{-7}} = 2.94 \times 10^8\ Pa$$

Weight requirements indicated that an aluminum internal support structure was desirable. The highest-strength aluminum commonly available (7075-T6) has a yield strength of 5.03 x 10^8 Pa, which is less than twice the magnetic pressure loading the structure. Thus, a solid internal support structure was required, since even the smallest internal hole would double the stress, taking the structure past yield:

$$\sigma_\theta = p = 2.94 \times 10^8\ Pa$$

TEXMAP analysis of the first stage at peak current, the results of which are shown in Fig. 2, indicated that the peak air gap flux density was just under 28 T, so the design calculation was accurate. The distribution of radial and axial forces in the armature, shown in Fig. 3 and 4, respectively, were then incorporated into an ABAQUS model of the armature. Perfectly plastic material behavior was assumed for the armature winding, the mechanical properties of which were determined at CEM-UT through tensile and compressive tests. The original and displaced mesh for this model is shown in Fig. 5, with the displacements magnified by a factor of 53. The rear of the armature is at the bottom of

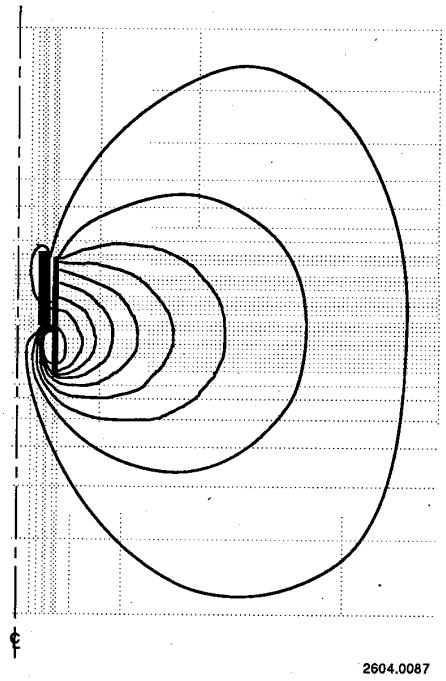

Fig. 2. Magnetic flux distribution in DCA launcher (stage 1, peak current)

the mesh, while the centerline of the gun is at the left edge of the mesh. The hoop stresses developed in the armature are shown in Fig. 6, where the peak compressive stress in the armature is at the outer rear radius of the support structure, and has a magnitude of 3.0 x 10^8 Pa. This is clearly in close agreement with the design calculation (2.94 x 10^8 Pa). The resulting 0.225 kg armature design is shown in Fig. 7. It incorporated an aluminum litz wire/epoxy winding, Nylatron front and rear bore riders, and a thin (~ 1 mm) fiberglass insulation sleeve between the potted litz wire and the aluminum support structure.

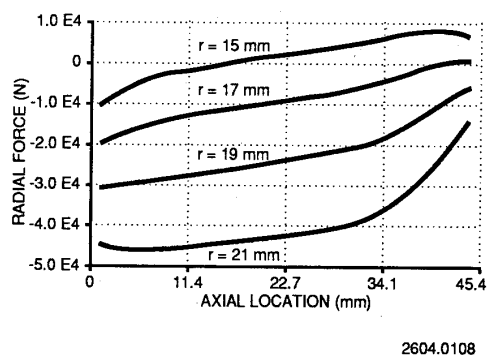

Fig. 3. Distribution of radial forces in DCA armature (stage 1, peak current)

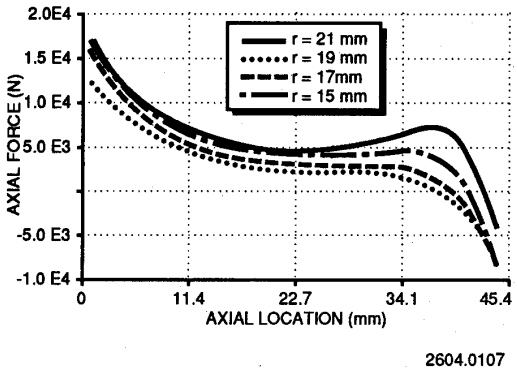

Fig. 4. Distribution of axial forces in DCA armature (stage 1, peak current)

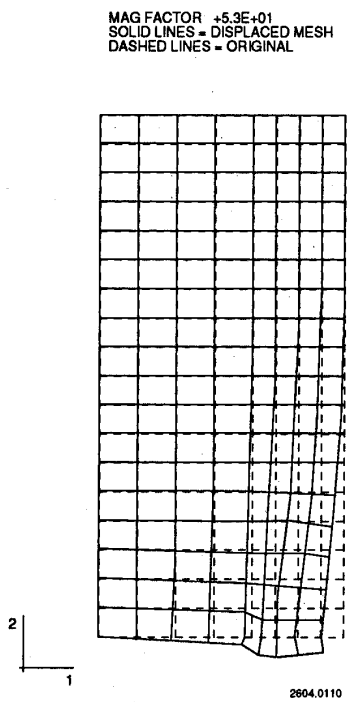

Fig. 5. FEM mesh for the DCA armature (stage 1, peak current)

Fig. 8 shows a comparison of predicted and measured plastic deformation of the armature winding in a full-energy one-stage shot. This shot accelerated the armature to 113.7 m/s with simulations showing a peak acceleration of approximately 130 kgees. Armature deformation was measured with the armature mounted between centers using a dial gauge. The finite element model clearly shows the trend of the plastic armature deformation, but underpredicts the magnitude of the deformation along most of the length of the armature.

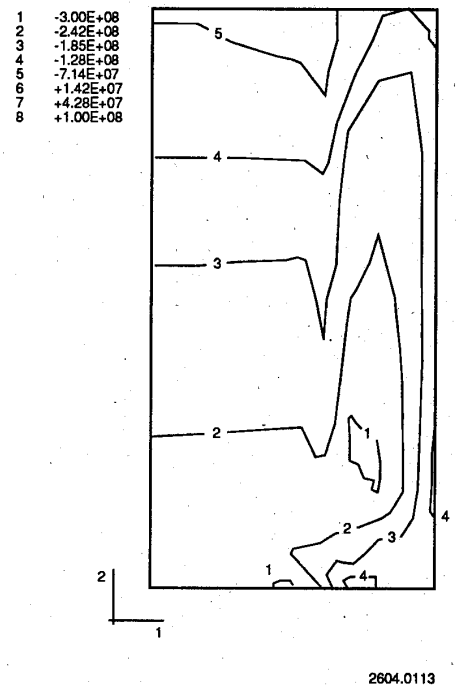

Fig. 6. Hoop stresses in the DCA armature (stage 1, peak current)

A total of nine armatures were designed and tested. The original design consistently failed at the rear Nylatron bore rider. As the designs evolved, stiffer rear end plates were added, starting with G10 and working through radially slotted titanium (to reduce circumferential eddy currents) and finally solid titanium. The only design that was repeatably able to survive a multiple-pulse full-energy launch was one which incorporated a solid titanium rear end plate. This end plate axially preloaded the armature winding via a 0.39 in. diameter titanium rod running down the armature centerline. The rod was press-fit (0.001 in. radial interference) into a hollow aluminum support structure, and bolted to the front Nylatron bore rider. The added mass of the titanium end plate and central rod raised the total armature mass to just over 0.25 kg. It should be noted that no discernible penalties in energy conversion efficiency occurred due to eddy currents in the titanium end plate.

Although the calculations have not been shown, the external support structure for each stator coil in the launcher was defined in a similar manner. These were built from hoop-wound S2-glass fabricated on CEM-UT's filament winding machine. S2-glass was selected for its high strength (S_y > 1.0 x 10^9 Pa) and low conductivity, to reduce eddy currents. To date, some of the DCA stator coils have been loaded almost three hundred times, with current levels ranging from 20 to 100% full current. None of the stages shows any visible sign of wear or fatigue.

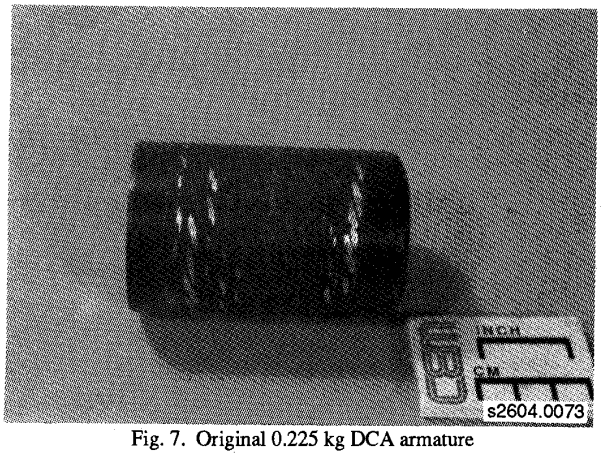

Fig. 7. Original 0.225 kg DCA armature

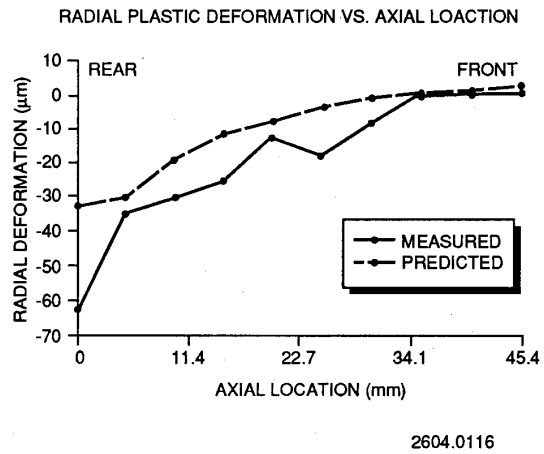

Fig. 8. Plastic deformation in the DCA armature for a full-energy, single-stage shot

Summary and Conclusions

Support structure requirements for generic coilguns have been defined as a function of launcher classification and acceleration mode. Closed-form hoop stress calculations have been presented that allow definition of the support structure requirements for a given winding. Design calculations for a pulsed induction launcher armature have been compared to finite element analysis. The plastic armature deformation predicted by this analysis has been compared to measured plastic deformation after a full-energy shot. Finally, the evolution of the armature design based on empirical evidence has been discussed.

Coilgun programs at CEM-UT have shown that, through proper design and analysis techniques, it is possible to construct lightweight, high energy coilguns. Although only the breech section of the DCA launcher was built and tested, the system successfully and repeatably accelerated 0.225 to 0.250 kg armatures to velocities as high as 300 m/s. These experiments can be accurately simulated, and simulations show this launcher's capability of accelerating the latest armature design to well over 1,000 m/s, using equipment identical to the five stages currently in place. It remains to be seen whether pulsed induction launcher technology is the best way to achieve such performance; however, the success of the DCA experiment indicates that this technology shows great promise.

Acknowledgments

The work described was conducted by CEM-UT and was funded by U.S. Army ARDEC under contract no. DAAA21-87-C-0247.

References

[1] S. Williamson, et al., IEE Proc., vol 133, Pt. B, no. 4, July 1986

[2] Widner, Melvin, 1991 IEEE EML Proceeding Page 634

[3] J.L. He, Z. Zabar, E. Levi, and L. Birenbaum, "Transient Performance of Linear Induction Launchers Fed by Generators and by Capacitor Banks," 1991 IEEE EML Proceeding, pg 585.

[4] Warren C. Young, "Roark's Formulas for Stress and Strain," McGraw-Hill, 6th edition, 1989, pp 638-639.

[5] Derek Hull, "An Introduction to Composite Materials," (Cambridge solid state science series), Cambridge University Press, 1981.

[6] D. A. Bresie, J. A. Andrews and S. K. Ingram, "Parametric Approach to Linear Induction Accelerator Design," Fifth EML Conference, Destin, FL, April 2-5, 1990.

[7] M. W. Ingram, J. A. Andrews and D. A. Bresie, "An Actively Switched Pulsed Induction Accelerator," Fifth EML Conference, Destin, FL, April 2-5, 1990.

[8] J. A. Andrews and J. Devine, "Armature Design for Coaxial Induction Launchers," Fifth EML Conference, Destin, FL, April 2-5, 1990.