Coilgun Technology At The Center For Electromechanics, The University Of Texas At Austin

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Abstract—This paper describes the engineering trade-offs performed on a coilgun design at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). The concept used was that of a collapsing field accelerator. This concept was chosen because of its passive operation, and because it lent itself to existing power supplies. The trade-offs described, however, should be performed on any concept in order to achieve a successful design.

The trade-offs described in the paper concern stress, maximum temperature rise in conductors, efficiency, time constants of energy storage element, and weight. An example of such a trade-off concerns the mass of coilgun armatures. The more massive an armature, the greater its ability to absorb resistive losses and the higher its time constant. However, larger armatures lower payload efficiency. Another trade-off concerns the fraction of armatures weight that is devoted to structure. More highly stressed armatures have more attractive electrical performance at the expense of parasitic weight. These and other trades are discussed.

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INTRODUCTION

Coilguns are electromagnetic accelerators consisting of stationary solenoid coils (stators), which create a magnetic field for propelling a moving coil (armature). Scientist and engineers have recognized the potential uses for these coilguns for many years. On paper, they seem to overcome many of the disadvantages of railguns, two conducting parallel rails shorted with a sliding armature. The coilgun requires no sliding contacts and the muzzle arc frequently seen on railguns is absent. More importantly, a coilgun, being a many-turned device can have considerably higher inductance than railguns. This makes matching to a power supply more convenient.

In a coilgun, forces exerted by the stator and armature on each other are well understood. They are characterized by the current in each and by the variations in the mutual inductance between them. The mutual inductance can be determined using the tabular methods described in works such as Grover [1] or in closed form using the methods of S. Williamson [2]. Both assume that the various coils of the gun are divided into an array of very small conductors called filaments. Averaging the various mutual inductances of all these conductors is the filament method. The filament method works well in predicting the performance of a coilgun connected to a power supply. Computer programs for simulating coilgun performance in this way are available at several sites:

Sandia	-	Warp 10	[3]
JPL	-	Mesh Matrix	[4]
CEM-UT	-	Axi coil	[5]

These codes are computationally very intensive and usually run on supercomputer main frames. At CEM-UT, the simulation codes have been improved to reduce run time. This allows rapid evaluation of coilgun concepts.

Many types of coilguns have been proposed over the last decades; several concepts have been described at the Electromagnetic Launch Conferences and at the Pulse Power Conferences. Most of these papers deal with matching power supplies and power conditioning equipment to the gun in an effort to have a practical and efficient accelerator. These papers predict attractive performance for several concepts. However, because of the general complexity of coilguns, few concepts have been reduced to working hardware of any significant size.

Engineers at the Center for Electromechanics at The University of Texas at Austin have participated in several coilgun projects:

Hypersonic Real Gas Facility - NASA
DC Coaxial Accelerator - Army
EM Accelerator - Navy
Rising Frequency Generator - Army
Linear Coilgun - Army

Early studies concentrated on simulation of various concepts. Later work involves fabrication and test of prototype coilguns. The overall outcome of this work has taught that achieving a successful coilgun design depends on successful solutions to sensitive engineering trade-offs. Stress, ohmic losses, peak fields, launch time, power, and efficiency are all very much interrelated. To obtain a coilgun with performance greater than powder guns, a design must be found that optimize each of these parameters. This paper describes some of these trade-offs.

COILGUN BASICS

In his paper "Theoretical Analysis of a Collapsing Field Accelerator,"[6] S. K. Ingram describes the operation of a coilgun in terms of flux linkages. For a single stator coil and an armature coil, the following relationship exists.

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$$\begin{bmatrix} L_s & M \\ M & L_a \end{bmatrix} \begin{bmatrix} I_s \\ I_a \end{bmatrix} = \begin{bmatrix} \lambda_s \\ \lambda_a \end{bmatrix} \tag{1}$$

where,

L = coil inductance

M = the mutual inductance between coils

I = current

λ = flux linkages.

The subscripts a and s refer to the armature and stator respectively. If the concept of a non-dimensional coupling coefficient is introduced:

$$k = M / \sqrt{L_a L_s} \tag{2}$$

then the magnetic energy stored in the pair of coils can be expressed as,

$$E_m = \frac{1}{1-k^2}\left(\frac{\lambda_s^2}{2L_s} + \frac{\lambda_a^2}{2L_a} - \frac{k\lambda_a\lambda_s}{\sqrt{L_a L_s}}\right) \tag{3}$$

The first term in the bracket is the self energy of the stator, the second term is the self energy of armature, and the third accounts for mutual compensation. The conversion of magnetic energy to kinetic energy in a coilgun stage can be determined by evaluating the magnetic energy before and after the conversion process.

$$E_{Kin} = E_m|_1 - E_m|_2 \tag{4}$$

where 1 and 2 are the two armature positions between which the energy conversion occurs. It is interesting to notice that, in the absence of ohmic losses and drag, the process is completely independent of the intermediate states between states 1 and 2, and that the process is completely reversible.

Equation 3 also gives valuable insight about the classification of various types of coilguns and their efficiencies. In coilguns with induced armature current and a pulse power supply [3],[5], the armature has no initial flux linkage and attempts to exclude flux during the conversion process. Equation 3 reduces to:

$$E_m = \frac{1}{1-k^2}\frac{\lambda_s^2}{2L_s} \tag{5}$$

By taking state 1 to be the position in which the coils are centered on each other and by taking state 2 as a remote location,

$$k_1 = k_o \ \ and\, k_2 = 0 \tag{6}$$

Equation 4 becomes

$$\begin{aligned} E_{Kin} &= \frac{1}{1-k_0^2}\frac{\lambda_s^2}{2L_s} - \frac{\lambda_s^2}{2L_s} \\ &= \frac{k_0^2}{1-k_0^2}\frac{\lambda_s^2}{2L_s} \end{aligned} \tag{7}$$

Initial stored magnetic energy $E_m|_1$ is given by,

$$E_m|_1 = \frac{1}{1-k_o^2}\frac{\lambda_s^2}{2L_s} \tag{7.1}$$

Substituting 7.1 into 7 gives,

$$E_{KE} = k_o^2\, E_m|_1 \tag{7.2}$$

In as far as it is difficult to find stator armature coil pairs with a centered coupling factor greater than about 0.7, the maximum conversion ratio obtainable with a pulsed inductance accelerator is about 50%. This is also the maximum system efficiency obtainable without some kind of method to recover the energy left behind in the stator coils. In an induction type coilgun with a polyphase power supply, the solution for conversion ratio is much more complex since energy is being added and recovered during the conversion process. The polyphase supply provides built-in energy recovery.

In the pulsed synchronous coilgun as described by S. K. Ingram, the objective is to achieve a zero current in the stator coil near the centered position. Although this permits total conversion of stator magnetic to kinetic energy, considerable flux must link the armature to achieve this condition.

Contrast the 2 pulsed coilguns, the induced armature and the synchronous. The inducted armature is completely passive. Stator flux compresses the armature. Support structure if any is in the center of the armature, out of the way. This type of gun is generally simple, but in order to work well very accurate timing is required for the power supply pulses. The electric power delivered to the gun coils is generally much greater than the average mechanical output power. In spite of these limitations, pulsed induction coilguns deserve continued development because of their simple strong lightweight armatures.

The pulsed sychronous coilgun has the advantage of being completely passive and if properly designed can have gun efficiencies near 100%. It suffers from the need to have a powered armature. The armature energy in the CEM-UT design is introduced prior to launch and the current, free-wheels during the launch. The stresses in the armature are tensile. This makes it very difficult to provide adequate stuctural support without adversely affecting the coupling coefficient. One of the most important advantages of this kind of coilgun is that the electrical energy can be put into the barrel parior to launch. The supply power can be lower than the average gun power. This energy conditioning effect makes for smaller power supplies.

CEM-UT has recently completed investigations of a pulsed induction coilgun [5] and is currently studying a pulsed sychronous type coilgun which we call Sychronous Passive Attraction Accelerator (SPEAR).

As described in table 1, the coilgun has the following target performance goals:

TABLE 1. TARGET PERFORMANCE GOALS

Bore:	120 mm
Length:	8 M
Projectile Weight:	2 kg
Muzzle Energy:	4 MJ

The gun is to be powered with the existing Iron Core Compulsator at CEM-UT at a rate of about 200 Mwatts. Completion is scheduled for 1994.

LIMITATION OF COILGUNS

While computer simulations have successfully demonstrated the feasibility of several kinds of coilguns, the success of a coilgun lies inthe solution of the detailed engineering. Stress, heating, and efficiency play important roles in the design. While high efficiency of an accelerator is not of primary importance in and of itself, efficiency does determine the power supply size, weight, and cost.

Many engineering problems must be solved for a successful design. Three problems are particularly troublesome because they require compromises in the design. As the launch progresses, current in the armature heats the conductor. The heating must be kept below what is allowed by the conductor and insulation material. This is done by minimizing energy stored in the armature, minimizing launch time and by having a relatively high armature conductor weight. Stress on the other hand is controlled by increasing launch time, minimizing conductor weight, and by reducing energy stored in the armature. Good efficiency requires a low stator coil resistance and low armature resistance. Table 2 shows the trades.

Heating

Heat generated in the armature is,

$$H_a = \int (Ni)^2 R_o dt \tag{8}$$

where,

Ni = ampere turns in the armature,

R_o = equivalent single turn resistance

t = time. But,

$$\begin{cases} Ni = Ni_o e^{-\frac{t}{\tau}} \text{ and} \\ \tau = \text{the armature time constant, } L_o / R_o. \end{cases}$$

L_O = armature single turn inductance.

The magnetic energy stored in the armature is,

$$E_a = \frac{1}{2} L_o (Ni)^2 = E_{ao} e^{\frac{-2t}{\tau}}$$

Substituting in 8 and integrating, we get:

$$H_a = E_{ao} \left[1 - e^{\frac{-2t_l}{\tau}} \right] \tag{9}$$

For loosely coupled stator coils, muzzle energy is,

$$E_m = k_o^2 E_{ao} \sum_{i=1}^{n} e^{\frac{-2t_i}{\tau}}$$

where, t_i is the time in each of the n stages and,

$$t_i \approx t_l \left(\frac{i}{n} \right)^{\frac{1}{2}}, \quad t_l = \text{launch time}$$

this can be approximated by,

$$E_m \approx k_o^2 E_{ao} \int_o^N e^{-\frac{2t_l}{\tau}\left(\frac{i}{n}\right)^{\frac{1}{2}}}$$

$$= k_o^2 E_{ao} N \left[\frac{1}{2} \left(\frac{\tau}{t_l} \right)^2 \left(1 - \left(1 + \frac{2t_l}{\tau} \right) e^{-\frac{2t_l}{\tau}} \right) \right] \tag{10}$$

TABLE 2. TRADES

	When Armature Conductor Weight Increases	When Stator Thickness Increases	When Launch Time Increases
Armaure heating	reduces	increases	increases
Armature stress	increases	increases	decreases
Gun efficiency	increases	increases	decreases

The terms in the brackets is called the gun conversion factor η_g.

Muzzle energy will be slightly less for tightly coupled stator coils. Substituting 10 into 9, we get,

$$H_a = \frac{E_m}{k_o^2 N \eta_g}\left[1 - e^{-\frac{2t_l}{\tau}}\right] \tag{11}$$

but muzzle energy is,

$$E_m = \frac{1}{2} M_p v_m^2. \tag{12}$$

where,

v_m = muzzle velocity

We can make armature conductor a fraction of the launch mass, M_p.

$$M_c = f M_p \tag{13}$$

Heat capacity is as a function of specific heat, c_p is,

$$H_c = M_c \int_{T_0}^{T_F} C_p \, dT = M_p P(T) f \tag{14}$$

Where P(T) is the heat capacity function. For a successful design:

$H_a < H_c$

From (11) let

$$R = \left[1 - e^{\frac{-2t_l}{\tau}}\right] \Big/ \eta_g$$

$$= \frac{\left[1 - e^{-\frac{2t_l}{\tau}}\right]}{\frac{1}{2}\left(\frac{\tau}{t_l}\right)^2 \left(1 - \left(1 + \frac{2t_l}{\tau}\right) e^{-\frac{2t_l}{\tau}}\right)} \tag{15}$$

For $\frac{t_l}{\tau}$ less than 2, R fits the equation

$$R = 3.0\left(\frac{t_l}{\tau}\right)^{1.5} \quad \text{very well.}$$

Substituting,

$$V_m = \frac{2l}{t_l}$$

and acceleration,

$$a = \frac{v_m}{t_l}$$

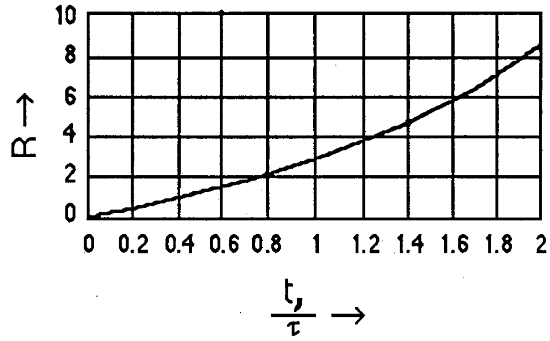

Fig. 1. R function vs. normalized time constant

and,

$$N = \frac{l}{b}.$$

(Effective stage length is 1 bore, b.)

Then the heat per unit of conductor mass is

$$\frac{H_a}{M_c} = \frac{3ab}{k_o^2 f}\left(\frac{t_l}{\tau}\right)^{1.5} \tag{16}$$

Heat capacity per unit of conductor mass is,

$$\frac{H_c}{M_c} = P > \frac{H_a}{M_c} \tag{17}$$

For aluminum conductor going from -200°C to 200°C,

$$P \cong 318 \, KJ / kg$$

Armature concepts can be tested against these relationships to determine if the armature is likely to survive thermally. Several approximations and simplifications were made to arrive at these relationships. While they provide a good guide for making trade-offs, the final design should be tested using more accurate finite element methods.

Armature Stress

Armature stress can be treated in much the same way as heating. A long solenoid approximation gives field density,

$$B_{ID} = \frac{\mu_o (Ni)}{l}$$

where the subscript ID means inside diameter, and l is the armature length. As a function of radius r from the centerline,

$$B(r) = B_{ID}\left[\frac{r_{OD} - r}{w}\right]$$

where,

w = conductor thickness

Magnetic pressure at a radius is,

$$p(r) = \frac{1}{2}B(r)\, J\,[r_{OD} - r]$$

substituting,

$$J = Ni/lw \qquad \text{(assume uniform)}$$

we get,

$$\sigma_{hoop} = \frac{\mu_o}{2}\left(\frac{Ni}{lw}\right)^2 [r_{OD} - r]\, r$$

The long coil approximation of the armature single turn inductance is,

$$L_o \cong \frac{\pi \mu_o \bar{r}^2}{l} \qquad (18)$$

Substituting for armature energy,

$$\sigma_{hoop} = \frac{E_a}{L_o}\mu_o \frac{[r_{OD} - r]\, r}{l^2 w^2}$$

$$= \frac{E_a [r_{OD} - r]\, r}{\pi \bar{r}^2\, l w^2} \qquad (19)$$

Armature stress can be treated in much the same way. In the armature, the magnetic field creates a repulsion force which manifest itself primarily as hoop stress. This hoop stress is reacted as tensile stress in the circumferential fiber of the conductor and in the support structure. Because of the composite nature of the armature, and because of the circumferential wound material, the hoop stiffness is much greater than the radial or longitudinal stiffness. For this reason magnetic forces are reacted mostly with hoop stress local to the conductor. For this reason, as an approximation, each incremental shell consisting of conductor and structure are generally self supporting. This assumption allows the computation of stored magnetic energy as a function of armature volume.

A long solenoid approximation gives field density,

$$B_{ID} = \frac{\mu_o (Ni)}{l}$$

where the subscript ID mean inside diameter and l is the armature length. As a function of radius r from the centerline,

$$B(r) = B_{ID} = \left[\frac{r_{OD} - r}{w}\right]$$

where,

w = conductor thickness.

The current density is,

$$J = Ni/lw$$

Pressure created on the incremental shell of the armature with a thickness of dr by body forces within that shell is,

$$p(r) = BJdr$$

Substituting,

$$p(r) = \mu_o \left(\frac{Ni}{lw}\right)^2 (r_{OD} - r)\, dr$$

But the thin wall pressure vessel equation requires,

$$\sigma(r)\, dr = p(r)\, r$$

or

$$\sigma(r) = \mu_o \left(\frac{Ni}{lw}\right)^2 (r_{OD} - r)\, r \qquad (20)$$

$$B_{ID} = \frac{\mu_o (Ni)}{l}$$

$$B(r) - B_{ID}\left[\frac{r_{OD} - r}{w}\right] \qquad \text{and}$$

$$J = \frac{Ni}{lw} \qquad \text{(constant)}$$

$$p(r) = B \times J \times dr$$

Substituting,

$$p(r) = \mu_o \left(\frac{Ni}{lw}\right)^2 [r_{OD} - r]\, dr$$

but thin wall pressure vessel equation,

$$\sigma(r)_{hoop}\, dr = p(r) r$$

$$\sigma(r)_{hoop} = \mu_o \left(\frac{Ni}{lw}\right)^2 [r_{OD} - r]\, r \qquad (21)$$

The long coil approximation of the armature single turn inductance is,

$$L_o \cong \frac{\pi \mu_o \bar{r}^2}{l} \qquad (22)$$

The stored magnetic energy in the armature is,

$$E_a = \frac{1}{2} L_o (Ni)^2 \tag{23}$$

Substituting 22 and 23 into 20.

$$\sigma(r)_{hoop} = \frac{2E_a [r_{OD} - r] r}{\pi \bar{r}^2 l w^2}$$

But the volume of the armature is,

$$V = 2\pi \bar{r} lw$$

$$\sigma(r)_{hoop} = \frac{4E_a [r_{OD} - r] r}{V w \bar{r}} \tag{24}$$

The factor $\frac{[r_{OD} - r] r}{w\bar{r}}$ varies from zero to about 3 / 4 for most configurations at the inside boundary.

The stored magnetic energy density is

$$\frac{E_a}{m} = \frac{\frac{1}{4}\sigma_{max}\frac{4}{3}}{p}$$

where p = density.

For a material with a composite strength of 200,000 psi. (carbon graphite and aluminum), and a specific gravity of 2.

$$\frac{E_a}{m} = 230 \text{ kj/kg} \tag{25}$$

It is interesting to note that stress is maximum on the inter bore of the armature and reduces to zero on the outside radius. If the mixture of structure and conducture is varied across the radius, placing most structure near the bore, then the energy density can probably be improved by as much as double. This would depend on complex manufacturing procedures.

Maximum hoop stress on the inside surface is,

$$\sigma_{max} = \frac{E_a r_{ID}}{\pi \bar{r}^2 l w} \tag{26}$$

the volume of the armature is,

$$V = 2\pi \bar{r} l w$$

$$\sigma_{max} = \frac{2E}{V}\left[\frac{r_{ID}}{\bar{r}}\right] \tag{27}$$

Once again several approximations have been made, in particular the long coil approximation. Nevertheless, this equation is good for concept evaluation

Efficiency

The charging efficiency of the stator of the gun depend strongly on the thickness of stator windings. The thicker these windings are, the lower is the resistance and the less are the resistive losses in the charging process. Making the winding thick, however, reduces the coupling coefficient between the stator and the armature. This lowers the gun efficiency and increases the energy that the armure is required to store. In much the same way as in the sections on armature heating and armature stress, overall efficiency can be determined as a function of armature weight, stator thickness and a launch time. By trading off these parameters against one another, satisfactory values of efficiency, stress, and heating can be determined.

Conclusions

Realistic designs of coilguns must balance limitations implsed by temperature use, stuctural stress, and efficiency. These limitations can often be expressed with simple equations which give good approximations of these variables. The simple equations then become the basis for tradeoffs which give designs which approach optimum. This paper has suggested approaches to defining coilgun variables and has suggested tradeoffs which need working on in order to achieve a workable coilgun design. The details of the tradeoffs depend on the requirements of the particular requirements. The approaches suggested are intended as a starting point for designers attempting conceptual designs of coilguns.

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