PARAMETRIC APPROACH TO LINEAR INDUCTION ACCELERATOR DESIGN

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

Publication No. PR-99
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Abstract: Past work on the design of linear induction accelerators has centered on the development of computer codes to analyze accelerator designs, using the current filament method. While these filament models are a very valuable tool for evaluating the performance of an induction launcher design, they provide little insight into the selection of dimensions, materials, and operation points for accelerators with interesting performance.

Described in this paper is a parametric approach to defining effective accelerator designs. This method uses a computer optimization routine to iteratively seek out effective designs. The optimization routine is forced to search within a parameter space restricted to interesting and realistic parameters such as size, weight, voltage, and temperature rises. A filament model is used as the filter for the optimizer.

Several linear induction accelerators have been designed using this method. The accelerators designed all used a switched capacitor power supply. While the run time of this code on The University of Texas' CRAY XMP-24 computer is moderately long, the resulting designs have good predicted performance. With realistic power supplies and materials, accelerator efficiencies in the 20 to 40% range were easily obtained. This paper describes the effect of armature diameter, length-to-diameter ratio, and weight, as well as other parameters, on the optimum accelerator design.

Introduction

Linear electromagnetic accelerators have attracted the interest of scientists and engineers for many years. Periodically, they have investigated coaxial accelerators, also called coil guns, as weapons systems. Egeland [1] describes such an attempt by Birkeland as far back as 1901. Many studies have been conducted on coil guns since that time, concentrating on the development of the mathematical and computer tools needed to analyze various coil gun concepts. At the Center for Electromechanics at The University of Texas at Austin, (CEM-UT), one such program concerned the use of variable frequency, polyphase generators as power supplies for coil guns [2]. In another study at CEM-UT, various linear coaxial accelerators were compared as candidates for weapons launchers.

The method described here was developed as a design tool for the Direct Current Coaxial Accelerator program. A goal of this project is the design of a practical high performance linear induction acceleration using a simple direct current supply.

Coil guns work on the principle of mutual attraction and/or repulsion of a set of coaxial coils, some fixed, others movable. The force produced between two coils, 1 and 2, in such an accelerator is described by the equation:

$$F_{12} = \frac{1}{2} i_1 i_2 M'_{12} + \frac{1}{2} i_2 i_1 M'_{21} + \frac{1}{2} i_1{}^2 L'_1 + \frac{1}{2} i_2{}^2 L'_2, \quad (1)$$

Where,

$$L' = \frac{dL}{dx} = \text{self inductance gradient}$$

$$M' = \frac{dM}{dx} = \text{mutual inductance gradient}$$

Typically, these forces are evaluated using the current filament method [3]. With this method, the coils are divided into a large number of conductors, which may be treated as filaments of infinitely small diameter. Thus divided, the inductances of the filaments can be calculated in closed form or determined from simple tables. This technique provides a very accurate simulation of the performance of a coil gun. The limitation of the method is that it offers little insight into what dimensions and power supply characteristics provide a high performance accelerator. The large set of design parameters makes it difficult to logically iterate through a series of designs.

Parametric Analysis

The problem is to design a coil gun with interesting performance. Efficiency must be high. Heating of the parts must be realistic, stresses must be manageable, and size must be reasonable. The number of possible choices for coil-gun parameters is limitless. Since the simulation of a design is computationally time intensive, an efficient optimization routine was needed to arrive at a good design within the limits of reasonable resources. The basic approach of the work presented here was a computer program which iterates the coil-gun design to optimize performance.

The configuration that was selected was an air-core, single stage coil gun, powered by a switched capacitor power supply. Both the stator coil and armature coil are assumed to be wound, multiturn designs. The parameter space is very large. Some of the major parameters are shown in table 1.

A computer code was written using one of the standard Fortran optimization routines in the Harwell Library at the Center for High Performance Computing at The University of Texas at Austin (UT-CHPC). The code for the simulation of the single stage coil gun was used as a filter for the optimization routine. In other words, the code tries a set of parameters and simulates the guns performance. By individually varying each parameter, and resimulating the guns performance, the code can logically proceed towards an optimum design. This continues until some optimization criteria is satisfied. The convergence of the solution is made more rapid by also computing the derivatives of performance with respect to each parameter, which determines the proximity to an optimum design (all derivatives are zero).

Table 1. Major parameters

Dimensional

1. Gun bore or stator coil inside diameter.
2. Armature outside diameter or air gap.
3. Stator and armature lengths.

Electrical

1. Turns in the stator and armature coils.
2. Stored energy in the power supply.
3. Power supply impedance.

Operational

1. Offset of the armature at stator turn-on.

Initial Conditions

1. Armature and stator initial currents.
2. Armature velocity.
3. Armature and stator initial temperatures.

Materials

1. Armature and stator coil conductor materials.
2. Allowable stresses.
3. Allowable temperature rise.

In theory it does not matter what initial guesses for the various parameters are used. There is a danger, however, that there are local minimums (or maximums) which may fool the program into a false solution. For this reason, initial values for the various parameters are chosen in a window of interest. As an example, initial gun bore is not chosen as zero since that value of bore is of no interest. Also, it is necessary to constrain each parameter which is allowed to change. This prevents solutions which are outside of the area of interest. For example, coil guns of only a limited range of bore sizes are of interest for this study.

A difficult decision concerns what optimization criterion to use. Maximum velocity is an attractive choice; so is maximum kinetic energy gain. It was thought that these criteria might lead to trivial solutions, which were of little interest because of size, cost, or low value as a weapon. As a compromise, stage efficiency was chosen as the optimization criteria. This choice enabled us to explore a relatively large area of interest. As a practical matter, other optimization criteria can be used once the area of interest is narrowed. Three other interesting criteria are minimum weight, minimum cost, and maximum percent payload.

The overall goal of the program was to design a coil gun with a projectile mass of at least 100 g and a muzzle velocity greater than 2 km/s. Using this goal, the area of interest for an optimization run was narrowed considerably. The projectile weight dictated a range of bore diameters from about 2 to 5 cm. Other constraints were fixed in order to conform to limits of material availability or safety.

One of the most troublesome aspects of the design of a high performance coil gun is armature heating. Elliot [4], Cowan [5], and others have indicated that velocities of induction coil guns are limited by armature heating. This problem is especially pronounced in monolithic armatures in which the trailing edge carries the majority of the current. In order to reduce this effect, an assumption of transposed windings in the armature was made. The mechanical design of transposed winding armatures is the subject of another paper. For the purpose of this work, it is sufficient to say that designs do exist which allow us to make the assumption of a transposed winding.

Results

After a realistic table of constraints and limits were generated, the optimization code quickly converged on a solution. Figure 1 shows the results as a function of the number of passes through the optimization routine.

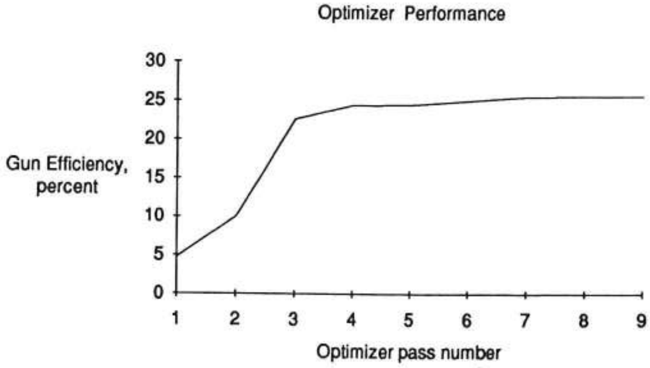

Figure 1. Convergence characteristics of the optimization routine

It is interesting to note that the code sometimes makes a wrong guess, which gives poorer results, but the mistake is usually corrected in the next iteration.

After the optimization run was complete, the computer generates a CAD picture of the resulting coil gun dimensions. An example of such a drawing is shown in figure 2.

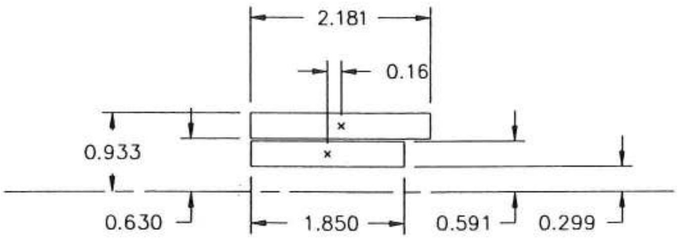

Figure 2. Gun configuration

A secondary benefit derived from the use of the computer code is that for the first time the effect of various parameters on gun performance can be studied. The effect of varying a gun parameter can sometimes be hidden if one does not look at optimum designs. For example, if optimum designs of different bores are compared, it is clear that gun efficiency improves as bore size increases. A summary of a gun bore investigation is shown in figure 3.

Bore Diameter (mm)	Stage Effiiency (%)	Entrance Velocity (m/sec)	Entrance Temp. (K)	Exit Temp. (K)	Peak axial Field (T)	Projectile Mass (g)
30	25.6	1414	522	536	30.9	100.00
45	48.2	1414	522	530	24.7	337.50
60	55.5	1414	522	526	16.8	800.00

Design veloicity = 2000m/s
Capacitor size = 125 mfd at 20 kv

Figure 3. Gun bore investigation

Additional information was obtained regarding the effect of armature temperature rise on gun performance. The allowable temperature rise is a function of the number of stages in a gun. The number of stages required is a function of the efficiency. Because of this interdependence, it is necessary to perform an additional iteration of the optimizations in order to obtain the correct initial conditions. Figure 4 shows the efficiency of the gun as a function of allowable temperature rise. Note that the diagonal straight line is the melt line. To the left of the line, the armature windings will survive the total launch; to the right they melt before reaching 2 km/s. The intersection of the diagonal with the curve is the maximum allowable temperature rise in an armature during transition of a stator coil.

Conclusions

Some of the results of the optimization runs were as expected, others were not. It was anticipated that armature outside diameter would always increase to the limit imposed by constraints. This is because the smallest gap between the armature and stator yields the best coupling. The optimizer confirmed this theory. The long, thin shape of the armature and stator coils were not so obvious prior to optimization. Nor was the result that armature and stator coils always converged to approximately the same length.

In the end, the optimization routine performed exceptionally well. Typical efficiencies of designs simulated prior to the optimization runs were in the 10 to 25% range. It is doubtful that improvement beyond this range could have been obtained through trial and error methods. With the aid of the optimization code, it appears that building coil guns with an overall efficiency around 50% is possible even without recovering the energy left in each stator coil after the armature passes.

Armature heating is still a serious problem in induction coil guns but appears to be manageable. There are still limitations of maximum gun velocity imposed by this heating. However, it now appears that velocities well over 2 km/s can be obtained without melting. There appears to be a very distinct trade off between armature heating and efficiency. Longer guns with a large number of low energy stages, result in less armature heating. This allows for higher muzzle velocity, but at the expense of overall efficiency.

The final outcome of the optimization work was a coil-gun stage design which has an efficiency of almost 50% and manageable heating and stresses. A prototype of this stage was fabricated and initial tests performed. Although testing of the prototype stages has just begun, preliminary results indicate that performance will be close to predictions. Figure 5 shows the prototype coil-gun stage.

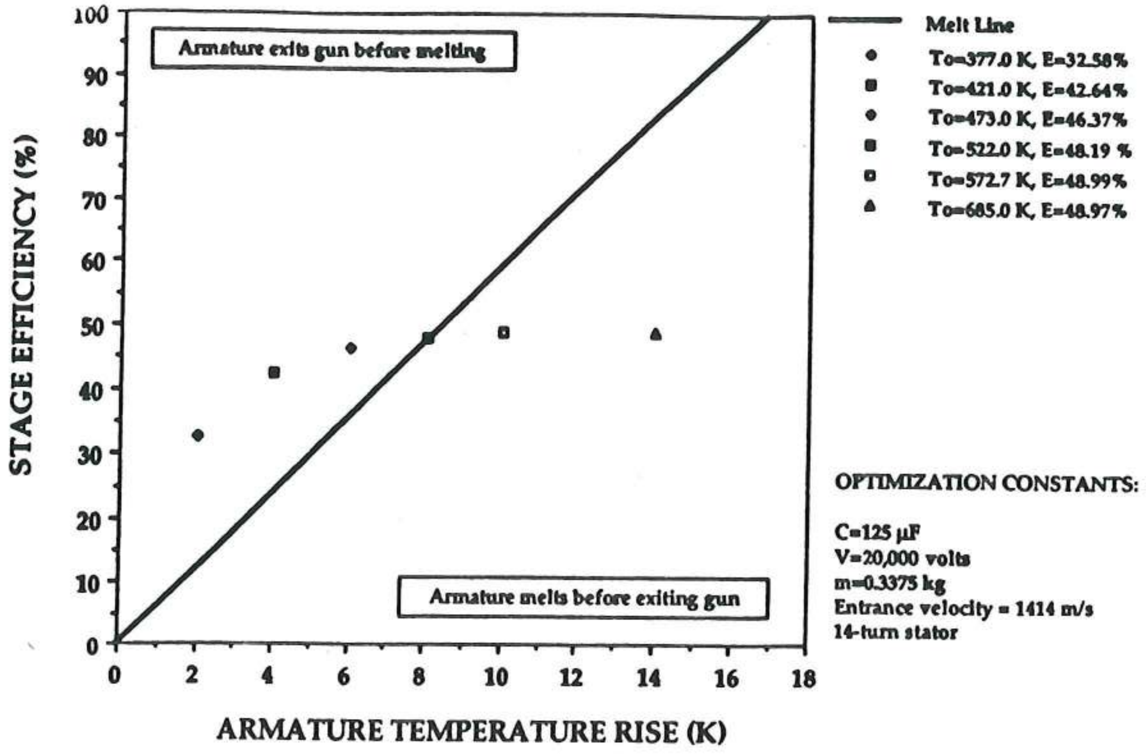

Figure 4. Armature efficiency vs. temperature rise, 45-mm gun

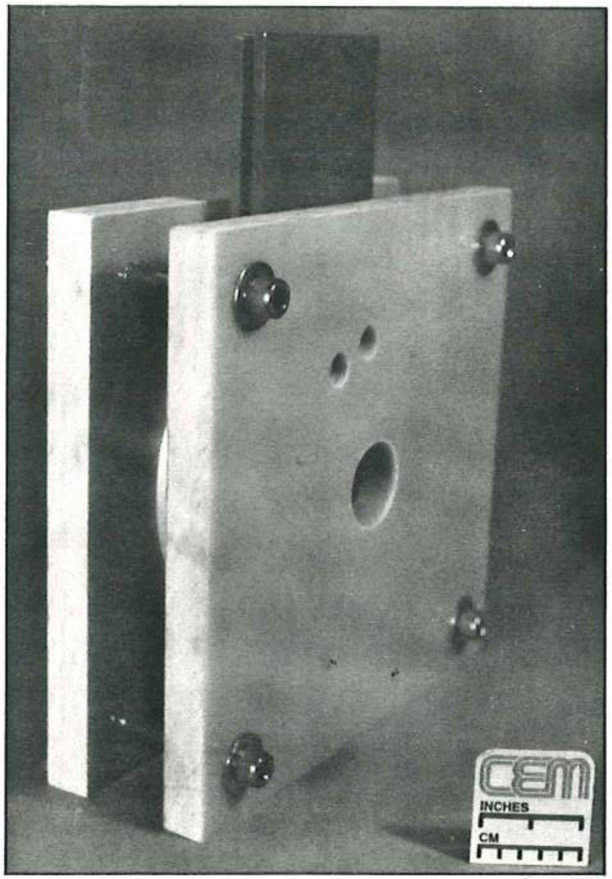

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Figure 5. Coil-gun stage

Acknowledgments

This work was performed as part of a contract by the U.S. Army Armament Research, Development, and Engineering Center and Defense Advanced Research Projects Agency, Picatinny Arsenal, NJ. This research is supported by The Department of the Army, U.S. Army, AMCCOM, under Contract No. DAAA21-87-C-0247, Karen Gubash, Contract Monitor Representative.

Mr. Richard W. Cook, formally at the Center for Electromechanics at The University of Texas at Austin, made a significant contribution to the development of the optimization code described in this paper.

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