AN ACTIVELY SWITCHED PULSED INDUCTION ACCELERATOR

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Abstract: A coaxial accelerator which will launch a 45 mm diameter, 225 g-mass to 2,000 m/s is described. The launcher is a true induction device, as no current feed to the armature is provided. The armature is a multiturn design, which forces a uniform current density and prevents excessive heating at the rear of the armature.

To meet the 450 kJ launch goal, the accelerator is composed of 47 separate stages. Each stage has its own capacitor power supply, which is discharged upon arrival of the armature. The system uses a "sense and switch" approach to ensure correct timing of the power supply discharges. In-bore armature position is detected using fiber optics; the necessary signals are fed into a programmable controller, which determines the velocity. Using this calculation, the controller determines the ideal time to fire the next stage and initiates the discharge at the appointed time. The accelerator described here is roughly 38% efficient (kinetic energy/stored energy) with a bore diameter of 45 mm. Simulations indicate efficiencies over 55% are possible with a 60 mm bore launcher and continue to increase with larger bore sizes.

This paper discusses the launcher and armature designs, power supply, and controls. Predicted performance of a five-stage launcher currently being built is presented. Experimental results from single-stage tests are presented and compared to simulated results. Solid (monolithic) and multiturn (wound) armature tests are also described.

Introduction

Most coaxial accelerators that have been proposed and built are either brush-fed or induction configurations. The former uses brushes on the armature to transfer the current from a set of stationary rails in the bore of the launcher into the armature [1] or to commutate the current from the stator coils into the armature and back into the stator.[2] While these designs can offer a very high efficiency (at least for velocities where brush operation is effective), they do not overcome one of the principle drawbacks of the railgun: the sliding electrical contact. Removing the brushes from the barrel affords the advantages of reduced bore wear, heating, and frictional losses. It also eliminates any velocity limitations imposed by the sliding electrical contact; the ultimate velocity is then limited only by ohmic heating in the armature.[3]

An induction launcher eliminates this sliding contact. The ideal configuration for such a gun uses a passive power supply, which produces a traveling magnetic wave, without switching or external power conditioning. Presently, such devices have only been proposed [4,5], since the power supplies do not exist. In an effort to develop a launcher likely to be used as a load for these power supplies, CEM-UT has selected a coaxial accelerator composed of discrete, independent coils.

Currently, CEM-UT is building a multistage induction accelerator designed to launch a 225-g armature to 2,000 m/s. For simplicity, each stage is driven by an individual capacitive power supply, requiring feedback control to properly sequence the discharges. A wound multiturn armature is used to control the heating and improve the efficiency over launchers with monolithic armatures.

An optimization code has been developed to aid in designing the accelerator, as the parameter space is too large and the functions are too complicated to effectively design an optimal accelerator without resorting to numerical techniques. The optimization and simulation codes have been compared to single-stage experiments at CEM-UT, as well as multistage experiments elsewhere [6], and agree quite well. The accelerator will be built in sections, with the first section reaching 605 m/s in five stages, which corresponds to a section efficiency of 33%. The individual stage efficiencies in this section range from 20 to 38%. All aspects of the design (peak current, magnetic field, acceleration, and stress), other than multistage operation, have been proven in single-stage tests.

Launcher Design Considerations

During the past few years, coaxial accelerator work at CEM-UT has been devoted to developing computer codes to model both air and iron-core launchers. In addition, a design code has been written that optimizes the efficiency of a single stage, subject to certain constants and constraints that bound the problem. This is a very important tool since the interaction between the launcher, power supply, and various physical constraints is rather complex. The optimization code allows the designer to compare optimal designs of launchers in which a single parameter (such as bore size or peak magnetic field) is varied. The code is sufficiently general to aid in the design of any type of coaxial air-core induction launcher. Slight modifications of the code allows investigations into brush-fed accelerators as well. If this single-stage code were not so computationally intensive, an attractive alternative would be a program that optimized an entire multistage launcher at once. This is impractical at this time, even with the Cray XMP/24 used for this design.

Details of the code may be gleaned from reference [7]; however, some must be mentioned here. The parameters which are varied to optimize efficiency are: armature and stator geometry (length, inner radius, and outer radius); armature position at initiation of stator discharge (firing angle); and power supply capacitance and initial voltage. Additional constants and constraints are: physical and electrical properties of the stator and armature windings; number of stator turns and other geometric constraints; stator and armature initial current and temperature; armature initial velocity; stator and armature maximum temperature rise; and total

launch mass. The code finds the combination of variables that yields the maximum efficiency without violating any of the constraints.

Several cases were studied in order to further understand the operation of an induction launcher, prior to settling on a design to meet the contract goals. It was found that in order to build a launcher that reached 2,000 m/s and just met the minimum required projectile mass (100 g), the bore diameter could not be greater than 30 mm. Such a small accelerator is rather inefficient (< 25%), due to the poor coupling between the armature and stator. After studying various bore sizes, it was found that 2,000 m/s could be reached at an acceptable efficiency of 48%, with a 45-mm bore and a 338-g armature (675 kJ). A 60-mm launcher with an armature mass of 800 g (1.6 MJ) was identified as having an efficiency of over 55%; however, the 45-mm bore was selected since it represented a good trade-off between efficiency and power supply size. Once the bore size was fixed, the armature and stator winding materials were chosen (aluminum and copper litz wire, respectively). The power supply for each stage was also fixed (a single 125 μ F, 20-kV capacitor).

The first detailed 45-mm design was reached by optimizing the middle stage first, since the middle stage would be more representative of an "average" geometry than either the breech or muzzle stages. Using an initial armature velocity of 1,414 m/s (half of the desired kinetic energy or the middle of the acceleration length) and an initial armature temperature of 522 K (halfway between room temperature and the melting temperature of aluminum), the optimization code again settled on a design with an efficiency of 48%. The efficiency was not very sensitive to the initial armature temperature, but was strongly affected by constraining the armature and/or stator to unrealistically small temperature excursions per stage. Once this design was set, a sensitivity study was undertaken to see the effect deviations of various parameters from their optimum would have on the launcher performance. Rather large perturbations in the power supply capacitance and voltage had little effect on efficiency; additionally, the number of turns on the armature was unimportant, as long as the amp-turns are held at the optimum (as determined by the code). The firing angle was varied to simulate the expected uncertainty of the velocity measurement system (< 2%). Virtually no penalty in performance was found.

Obviously, the armature geometry that is fixed at the middle stage must be used for all other stages. Using this code, each individual stator coil can be optimized subject to the common armature geometry and expected initial conditions. With the fixed armature design, the first stage was found to have an optimal efficiency less than 11%. Since this was low compared to the middle stage, the next approach was to optimize the armature geometry at the first stage and explore how this effects the middle stage.

The efficiency of the first stage improved to 20% when both the armature and stator were optimized at the breech. It appears that the first few stages of any induction launcher will always exhibit relatively low efficiencies, due to high slip at start-up (similar to rotating induction machines). The new armature length was shorter, which reduced the optimum mass to 225 g.

As each sequential stage was optimized, using the previous stage's final armature velocity, current, and temperature as initial conditions, it became apparent that the optimum stator geometries were virtually identical. Thus, the stator design was also fixed at the first stage, which allowed the code to explore only the variation of optimum firing angle for each successive stage. As the velocity climbed, stage efficiencies increased dramatically, and started fluctuating around 38% after four stages. The efficiency was still over 38% at the middle stage, but had dropped slightly to just over 35% at the muzzle.

Neither of these two design methodologies (optimum middle stage vs. optimum breech stage) appears to be clearly superior to the other. For this set of constraints (bore, power supply, mass, and materials) the former will probably result in a more efficient overall launch, at the expense of a more inefficient breech. Since the dominant cost in this type of accelerator is the power supply (the stator coils themselves are relatively inexpensive and easy to build), CEM-UT has decided to construct the first five stator coils using the optimum breech design. This allows immediate demonstration of a high-efficiency launch. In the future, these stator coils will be replaced with the less efficient design that uses an armature which becomes optimal near the middle of the launcher (~ stage 24).

Gun Design, Power Supply, and Controller

The stator coils are wound with transposed copper litz wire and are potted inside a composite tube (S2-glass). The tube is used to contain the large radial force on the coil occurring during a discharge; it also provides the terminations for attaching the buswork from the capacitors (fig. 1). The tube is sandwiched between two G-10 plates used for aligning the coils and transmitting the recoil force to the test stand. The test stand is also used to keep the coils in alignment.

Figure 1. A stator coil support structure with buswork attached

As stated before, a simple passively crowbarred capacitor bank is used to drive each stage. The capacitors are 125 μF at 20 kV (25 kJ each), with ignitrons as the switches. Presently, one capacitor per stage is used. The current is limited to 100-kA peak, with a rise time of 20 μs .

The accelerator and power supply will normally operate in a closed-loop or "sense-and-switch" mode. A block diagram of the closed loop controller is shown in figure 2. The projectile position is sensed upon exiting a stage. Two sensors located 1 cm apart along the axis of the launcher, each with a unique identification number, will detect passage of the projectile. The fire controller will determine the sensor location from the identification number, calculate the velocity, and determine the optimum firing angle for the following stage. The firing angle is found in a look-up table loaded into an EPROM prior to the shot; the table data is generated by the optimization code for the particular specifications of the experiment. The controller gives the command to fire the next stage based on the value found in the table, with a total throughput delay of < 300 ns. In the event the sensor identifications do not match the present stage (or each other), the experiment is shut down and the projectile coasts out of the launcher. Open-loop operation is also possible, with the controller firing each stage regardless of the armature position. This is the preferred mode if the performance is reliable.

Figure 2. Block diagram of the closed-loop controller

Presently, the capacitor banks have been built, the launcher is being built, and the controller has been built. Testing of the various components is underway. The simulated performance of a five-stage accelerator follows.

Predicted Performance

Figure 3 shows the current in the stator and armature for the optimized five-stage launcher. In figure 3(a), each stator coil has the same current direction, inducing a peak of 130 kA in the armature. Because the armature current reverses direction while the stator current does not, the armature is decelerated. This is known as magnetic braking [7] or armature capture. It has a cumulative effect on the performance, as the peak-armature current is steadily decreasing from stage-to-stage. A simple way to counter this is by reversing the polarity of the current in the next stator and changing the firing angle accordingly, taking advantage of the current still flowing in the armature. This type of configuration is hereafter referred to as a "PN" (positive/negative) launcher, as compared to a more conventional "PP" (positive/positive) launcher. Figure 3 (b) shows the result of this reconnection (the new firing angles are still optimum, as they were obtained from the design code). This simple change resulted in a more nearly constant peak-armature current and a higher efficiency. A comparison of the two configurations is shown in figure 4. The PN configuration reaches a velocity of 605 m/s at an overall efficiency of 33%. The PP configuration reaches 510 m/s at an overall efficiency of 23.4%.

Figure 3a. Stator and armature current for optimized design -- PP option

Figure 5 shows a scale drawing of the five stages (PN polarities), with the armature located at each correct firing position. Note that the stator winding is thin, while the armature winding is not. This is due to the heating

2604.0082

Figure 3b. Stator and armature current for optimized design -- PN option

2604.0083

Figure 4. Velocity for (a) PP option and (b) PN option

problems discussed earlier. Also, the firing position has changed considerably in the course of five stages. The rate of change has decreased somewhat by the fifth coil and will continue to do so (as long as the coils are as similar as they are in the first five stages).

An interesting point should be made about the size of the capacitors used for this design. If the capacitance per stage were doubled (250 μF) at the same voltage, the efficiency would drop by only 2%. Thus, the energy increment per stage would nearly double, considerably reducing the number of stages required to reach launch goals, although the total efficiency would remain relatively unchanged. The two main drawbacks are the increases in the peak field and the peak acceleration encountered in such a design.

2604.0084

Figure 5. Scale drawing of the five launcher stages, showing the armature at the firing position

Single-Stage Tests

In order to verify certain aspects of the launcher design and simulation, two prototype coils have been built and tested. The tests used both monolithic and wound armatures. An existing 1,100 μF capacitor bank with a 3-5 μH inductance was used for these tests. Full current (102 kA) was reached, as was full stress on the composite tube (110 ksi). An 96.3 g monolithic armature was launched at velocities up to 165 m/s. The coil efficiency (ratio of kinetic energy to total energy transferred to the stator coil) was 10.2%. In each case, the data matched well with predicted results for the monolithic armature. A multiturn armature (fig. 6) has been tested to 25 T (or 36 ksi) without damage to the windings. These were static tests, thus the armature was not allowed to move. A winding termination failed due to a poor solder contact, preventing further testing. A second armature is being fabricated and will be tested to find the ultimate magnetic field sustainable by the litz/epoxy material on the armature surface.

Figure 6. Multiturn armature used for preliminary tests

Conclusions

The design of a five stage induction launcher using a multiturn armature has been completed and the device is being fabricated. Testing on various components has begun and the multistage launcher will be installed early this spring. Expansion to 15 stages is expected in midsummer.

Considerable progress has been made in modeling linear induction launchers and determining design criteria for these devices. With the computer codes developed recently at CEM-UT, the optimum designs are comparatively easy to obtain. The parametric studies performed thus far have considerably advanced the understanding of the details of induction launcher performance and design and show its potential as a highly efficient, large bore, high-velocity accelerator. In addition to the experimental work being conducted, further study into the behavior of induction launchers is needed to accurately define their roles as high-velocity accelerators.

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