

DESIGN AND TESTING OF A 25-STAGE ELECTROMAGNETIC COIL GUN

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Abstract

Tetra has recently designed and fabricated a 25-stage prototype electromagnetic coil gun. To date, five stages have been successfully tested. Initial results track very well with predicted values. Each coil is sequentially fired as the projectile moves down the bore. A hybrid control system is used to measure the velocity of the projectile as it enters each coil and calculates the time-to-firing. Computer predictions based on this model indicate velocities greater than 3000 m/s can be achieved. Currently, the system has been tested with 10 kJ delivered to each coil. Solid dielectric switches are used to transfer the energy from each capacitor to the coils. Performance of the coil gun, computer modeling, and laboratory results are discussed.

Introduction

The Phalanx antimissile and the Vulcan anti-aircraft weapons systems are successful examples of high repetition rate, low projectile mass chemical based weapons systems. Electromagnetic based weapons are capable of achieving higher projectile velocities than chemical based weapons. Higher projectile velocities mean higher projectile energies for the same projectile mass.

Electromagnetic guns have been studied for many years by many different organizations. There have been two primary technologies which have been focused upon: railguns and electromagnetic coil guns. Rail guns have demonstrated impressive performance, but they have been limited by barrel wear due to brush contacts. Coil guns, on the other hand, do not have the limitations of barrel wear yet have run into obstacles associated with armature heating and crushing. To date, multistage coil guns have launched projectiles to velocities not exceeding 1000 m/s.

Tetra has developed an optimization method for the design of coil guns which increases the efficiency of the system and reduces the amount of stored energy required. After validation of computer models using Tetra's coil gun, projections have been made which show a velocity of greater than 3000 m/s can be achieved using information learned during the development of the optimizing method. A photograph of Tetra's coil gun is illustrated in **Figure 1**.



Figure 1. 25-Stage electromagnetic coil gun.

Design

Optimization method

Optimization of the coil gun is required to increase the efficiency of the system and to reduce the amount of stored energy required for each shot. Both of these items have a significant impact on the cost and size of the coil gun system.

We have investigated optimization of coil guns using the calculus of variations. This process leads to some interesting conclusions concerning the directions that designs should go. We have found a number of cases which can be solved analytically. An example is the case of optimizing the system for lowest resistive losses in the projectile. We can write the acceleration, a , of a projectile in a coil gun as:

$$a = - \frac{1}{2mL_p} I_d^2 \frac{\partial M^2}{\partial x} \quad (1)$$

where m is the projectile mass, L_p is the self inductance of the projectile, I_d is the drive current, and the last term is the gradient of the squared mutual inductance. An interesting observation is that three different components contribute to the acceleration of the projectile. One contribution is the projectile itself through its mass and self inductance. Another contribution is the drive current. The third contribution is the geometry of the coil/projectile system, the mutual inductance or more accurately the gradient of the mutual inductance (squared). When optimizing the system losses, one recognizes that the unrecoverable losses such as ohmic heating are proportional to the drive current. In equation 1, for a given level of force, drive current requirements can be reduced by decreasing the inductance of the projectile and/or increasing the gradient of the mutual inductance. The energy lost due to ohmic heating of the projectile is given by:

$$E_{\text{projectile}} = \int I_p^2 R_p dt \quad (2)$$

where I_p is the projectile current and R_p is the resistance of the projectile, taken to be a constant in this example. The projectile current can be written as:

$$I_p = -I_d \frac{M}{L_p} \quad (3)$$

It should be noted that constant acceleration guarantees the lowest peak acceleration forces on the projectile by the mean value theorem. Taking the acceleration as a constant, equation 2 can be rewritten as:

$$E_{\text{projectile}} = - \frac{2m a_o^2 R_p}{L_p} \int_0^{t_{\text{end}}} t \frac{dM^2}{dt} dt \quad (4)$$

where a_o is the constant acceleration, and t is time. Note that by letting $M^2 = e^Q$, where Q is a dummy functional, the equation is easier to work with. By using the calculus of variations, one can determine that the functional form of the mutual inductance which minimizes equation 4 is:

$$M^2(x) = M_o^2 e^{-hx^{\frac{3}{4}}} \quad (5)$$

where h is a positive constant for the family of minimal functional forms. The minimum projectile resistive loss energy can now be written as:

$$E_{\text{projectile}} = \frac{16mR_p V_f l_d^{\frac{1}{4}}}{9L_p h} \quad (6)$$

where V_f is the final velocity, l_d is the length of the acceleration stage.

The importance of this process is that, by the use of the calculus of variations, losses can be reduced by shaping the coupling between coil and projectile and by shaping the drive current. The resulting functional forms are not entirely intuitive. Additional optimization have been performed and will be presented in a future paper.

Computer model

Although our original intent was to design and build a fully optimized coil gun, budgetary constraints caused us instead to build a coil gun based upon existing capacitors and utilize lessons learned from the optimization study. To this end, we developed a computer code to model and predict the performance of a multistage coil gun. Initially, the code predicted the coupling between projectile, and then predicted projectile motion. This was used to optimize the system given the available capacitors. Once the system was built, the coupling was measured and input into the code. The code was then used to optimize the timing. The code has a realistic circuit model and calculates the coupled electrokinetic system of equations. Losses are accumulated and temperature dependent resistance and specific heats are utilized.

System

The coil gun consist of twenty five individual stages. A single stage consists of a series capacitor C_o , starter switch S_o , and coil L_o . A second switch, S_1 is placed across the capacitor C_o to crowbar voltage reversals. The RLC circuit that is formed is underdamped and tries to reverse the voltage across the capacitor C_o . Switch, S_1 is fired when the voltage on C_o approaches 500 V and protects the capacitor from voltage reversals. A typical current waveform rings up to 100 kA in 25 us and then decays exponentially to zero in 250 us.

A projectile is place in the breach end of the gun. The first coil is fired and the projectile is forced down the barrel. As the projectile move toward the second coil it crosses a laser beam which sends a signal to the timing and control hardware. The timing and control system measures the velocity of the projectile and calculates the necessary delay and fires the next stage and the projectile is accelerated again. The process continues through all twenty five stages with the projectile increasing in velocity through each stage.

High Current Density Coils

High current density coil construction was used to yield improved coupling between coil and projectile. A cross-sectional view of a coil is illustrated in **Figure 2**. The coils were constructed using compacted rectangular litz wire to achieve maximum packing and lowest resistive losses. The litz wire was wrapped with KAPTON insulation for voltage hold-off protection between turns. KEVLAR fiber was used to provide a mechanical restraint during energizing of the coils. KEVLAR fiber was used because of its unique high tensile strength capabilities. Once the coils were assembled, they were placed in a vacuum chamber and immersed in epoxy and potted. After the epoxy was cured, the coils were sent out for final machining of the bosses and fiber optic pilot holes. G-10 end plates were used in the construction of the coils. The coil assemblies were axially pre-loaded to 8 ksi by compressing the coil stack (barrel) to reduce movement of the coil

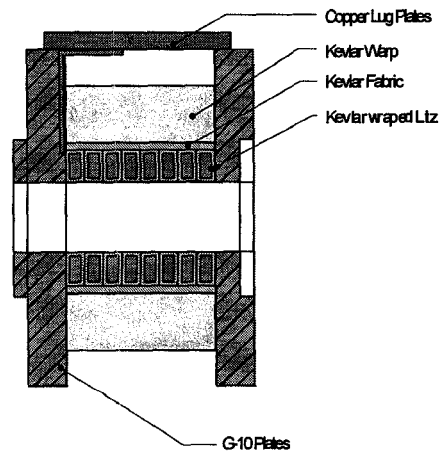


Figure 2. High current density coil.

windings during launch. Once the coils are in place a composite fly-way tube is inserted into the stack. The flyway tube was constructed of a woven fiberglass mat impregnated with a high temperature cure epoxy resin.

Laboratory measurements were made of the coupling between a projectile and the coil using a high frequency bridge. These results were compared with computer models generated using Nagaoka's's and Lyle's methods. Excellent agreement was achieved between the computer model and laboratory measurements. A curve fit of the spacial dependent coupling profile was created for use in the computer model.

Solid Dielectric Switches

Solid dielectric switches were selected for the coil gun for their high current carrying capabilities and low cost. The switches were not the first choice due to the time for turn-around during each shot, however, due to budgetary constraints they were justified for a proof-of-principle demonstration. Solid dielectric switches of this type have been demonstrated in other applications with great success (Ref. 1). The operation of the switch is straightforward, an insulating material, in our case KAPTON is placed between two sacrificial plates, one plate is bored to hold an exploding bridge wire (EBW), and the other is machined with a knife edge. Once the stage capacitor is charged, a capacitor discharge unit is discharged into the EBW, the wire explodes, blasting the KAPTON into the knife edge where it is cut and a plasma is formed between the two switch plates. Since switch jitter was a major concern for timing of the coil gun, we measured the jitter of the switch at 500 volts and found it to be less than 600 ns.

There are two CDUs for each stage capacitor, one for the starter switch and a second one for the crowbar switch. When the CDUs are fired, they float to the charge voltage of the capacitor bank. We designed a capacitor discharge unit which was battery powered and fiber optically triggered to completely isolate the units from the control system and ground.

Timing and Control System

The timing and control system incorporates fiber optic sensors for projectile location and velocity measurements. In a sequentially fired coil gun, stage timing is critical for maximum efficiency. A programmable controller was designed to analyze the optical signal and via least squares approximation based on analytical data, predict realtime optimum triggering for each stage. Instantaneous velocity measurements are processed and then stored so that projectile velocity profiles can be later recalled and analyzed for each shot.

Testing

Testing of the coil gun was conducted into a steel projectile trap. The trap was filled with cotton rags, corrugated cardboard, and sand partitioned into three separate chambers. A TDS540 digitizing oscilloscope was used for capturing all shot data. A 486/66 PC was used to program the timing and control and reduce shot data.

Diagnostics

Several diagnostics were used for gun testing. The detector signal coming from the laser diagnostics was used to measure projectile velocity. The projectile crosses a beam upon exiting each coil. The time the beam is blocked was measured and used with the projectile length to yield the exit velocity for each stage. A separate laser system was incorporated at the end of the barrel. The system was made up of three solid state laser diodes and three detectors. The laser detector pairs were spaced 10 cm apart. By measuring the time between the beam crossings for all three beams and averaging an accurate measurement of the exit velocity was obtained.

Rogowski coils were designed and built for measuring the current through each coil. The Rogowski signals were integrated and scaled to yield the current discharged through each coil. The Rogowski signals were used to determine if a prefire or pre-crowbar occurred during the shot. A multiplexer box was constructed which allowed the recording of 64 channels of data on a single 4 channel digitizer.

Performance Results

A maximum of five stages have been tested to date. The results from these tests yielded a velocity of greater than 200 m/s. The result from the laboratory tracked exceptionally well with computer projections. Several charge voltages (energy levels) have been tested and compared to computer projections as well. Once the computer model was validated with the laboratory results, projections were made with capacitors which more closely match design requirements.

Several tests were conducted for various stage numbers and charge voltages. Single stage 10 kV shots were tested first. A velocity of approximately 150 m/s was achieved with a single stage. A three stage shot was taken with a charge voltage of 8 kV which resulted in a final velocity of greater than 150 m/s. Finally five stage shots were taken at 6.5 kV charge voltage on each capacitor. A resulting velocity of 200 m/s was obtained. As the number of stages were increased, the charge voltage was lowered to increase the lifetime of the coils.

A plot of the velocity for each stage as measured in the laboratory compared with model predictions is illustrated in **Figure 4**. The excellent agreement between the model predictions and the laboratory results build a high level of confidence in the computer predictions for additional stages.

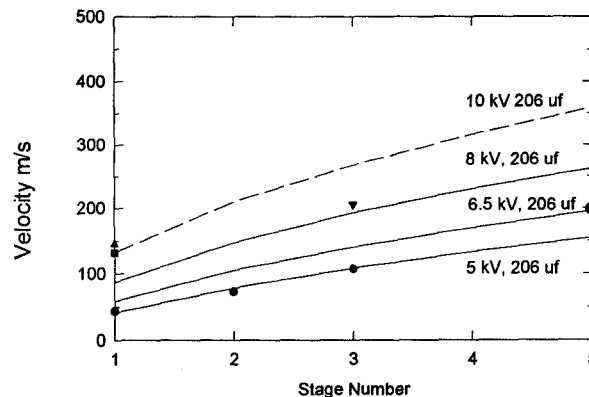


Figure 4. Comparison of model and laboratory measurements for various numbers of stages and energies.

Projections

Projections were made on the final velocity that can be obtained from all 25 stages. The projections yield a velocity of greater than 900 m/s at a charge voltage of 10 kV. An additional 100 m/s can be added if the projectile is initially cooled with liquid nitrogen. As has been mentioned due to budgetary constraints, we had to design the system around existing capacitors which greatly reduced the energy transfer efficiency of the system.

Computer models were generated for various capacitor values and energy levels for a thirty stage gun and the final velocity was recorded. Velocities in excess of 3000 m/s can be obtained with the correct capacitors matched to the system. A plot of the velocity performance for many of the configurations modeled is illustrated in **Figure 5**. This results confirms that the value of capacitors used on the present system are too high and most of the energy is dissipated in the coil after the projectile has left the usable field. One case which yields a high velocity for a minimum amount of energy occurs when a 34 kV, 52 μ s capacitor is used for each stage.

Conclusion

Tetra has developed a optimization method for the design of electromagnetic coil guns. The optimization increases the efficiency of the system and reduces the amount of stored energy required. To date Tetra has demonstrated 200 m/s velocity with five stages. Tetra coil gun model shows excellent agreement with laboratory results giving a high level of confidence in computer projection of an optimized system. A velocity of greater than 3000 m/s can be achieved from a 30 stage coil gun with the proper capacitor matching.

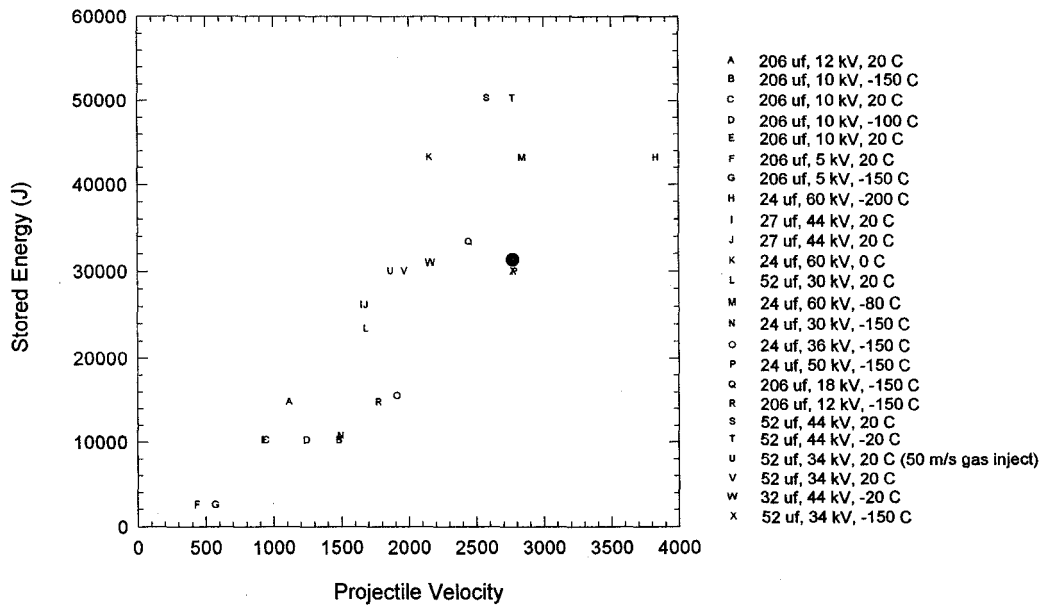


Figure 5. Computer projections for various capacitor and energy configurations. The vertical axis is the stored energy per stage and the horizontal axis is the final velocity for thirty stages.

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References

1. R.A. Richardson, W.R. Cravey, and D.A. Goerz, Performance of a 10 kV, 625 kA, 85 kJ Energy Discharge Module Utilizing a Solid Dielectric Switch. Presented at the 8th IEEE International Pulsed Power Conference, San Diego, CA.