1. Introduction

350 scientists and engineers from the United States and 60 other countries attended the 1992 Symposium on Electromagnetic Launch Technology at the University of Texas at Austin. This symposium was the sixth in the biennial series initiated in 1980 to provide a forum for presentation and discussion of research on critical technologies for accelerating macroscopic objects or projectiles to hypervelocities using electromagnetic (EM) or electrothermochemical launchers. Over 150 papers were presented at this symposium (see the January 1993 issue of the *IEEE Transactions on Magnetics* for more information).

The two main kinds of EM launchers are called rail guns and coil guns. In rail guns, a conducting projectile is placed between two parallel rails and a short high-current pulse is applied between the rails. The resulting magnetic field forces move the projectile along the rails, launching it with a very high velocity. A coil gun consists of a series of coils (solenoids) with the projectile placed inside. Applying a short high-current pulse to the coils produces magnetic field forces that move the projectile through the coils and launch it with a very high velocity. In both rail guns and coil guns the short high-current pulses are produced by charging banks of capacitors and then discharging them into the rails or the coils. In rail guns, current flows through the projectile and an arc occurs between the rails and the projectile, while in coil guns, there is no electrical contact between the coils and the projectile.

Conventional propulsion systems can produce launch velocities up to about 1.6 km/s. Rail guns have accelerated gram-size projectiles to almost 6 km/s. Researchers at the Sandia National Laboratories in Albuquerque, New Mexico (R. J. Kaye, et al., "Design and performance of Sandia's contactless coilgun for 50 mm projectiles," *IEEE Transactions on Magnetics*, vol. 29. January 1993, pp. 680-685) are designing a coil gun expected to produce velocities of 3 km/s in 50 mm diameter, 200 - 400 gram projectiles. These much

higher velocities are called hypervelocities. The Sandia launcher presently being tested consists of 40 stages. Each stage consists of a 30 μH coil, a 176 μF capacitor, a switch, and a cable. A laser-ranger tracks the location of the projectile in the launcher and switches each capacitor to discharge at the proper time to accelerate the projectile. The capacitors are charged by a 15 kV voltage source to store 20 kJ of energy. The Sandia researchers hope eventually to achieve velocities in the range of 4-6 km/s, which is sufficient to launch payloads into low earth orbit at reasonable cost. A 960-m long coil-gun launcher consisting of 9,000 coils could accelerate a 1200-kg launch package to deliver a 100-kg payload into low orbit.

Applications of EM launchers include a broad range of military applications, the launch of aircraft into flight, the launch of objects directly into space, and the acceleration of materials to extremely high velocities, either for ultrahigh-pressure or impact physics research or for the acceleration of fusile material to achieve impact fusion. An EM cannon could have a range of about 200 km, which means that 10 tanks with EM cannons properly deployed could cover an entire country of 450,000 square kilometers. Eventually, EM launchers might be used to launch toxic wastes into space. Spin-off of EM launcher research might lead to interplanetary vehicles using rail-gun-like plasma thrusters to eject hydrogen plasma at 100 km/s that could travel to Mars in two weeks with payload fractions similar to commercial aircraft, and hybrid gasoline-electric automobiles with acceleration like sports cars, but with lower fuel consumption, lower emissions, greater safety, and lower cost (M. R. Palmer, "Midterm to far term applications of electromagnetic guns and associated power technology," *IEEE Transactions on Magnetics*, vol. 29. January 1993, pp. 345-350). Although great progress has been made in developing EM launchers, the overall cost, weight and volume of power sources is still too great for many applications of the technology.

In this project, you will construct and test an EM launcher similar in many respects to the coil guns described above, but to avoid the time, expense, and danger involved in

constructing a device to launch larger projectiles, yours will be a miniature coil gun consisting of one small coil, and the projectile will be a short (3-4 mm) segment of wire from a standard paper clip. Because the magnetic forces on the projectile would force it to the center of the coil if a steady current were applied, you will need to design a circuit to produce a short current pulse, and to get sufficient force for launching, the current must be high. Therefore you will also design a circuit to discharge a capacitor into a coil to produce a short, high-current pulse. This project is but one example of many ways in which voltage and current pulses are employed in a variety of devices.

2. System Components

2.1 Coil construction. Procure a 3.0 cm nonmetallic tube with an inside diameter just slightly larger than the wire diameter of a standard paper clip, two nonmetallic disks about 2.5 cm in diameter, and five meters of 26 gauge insulated wire.

Precise design of the coil is too complicated for you to undertake in this short project, but here are some factors to consider. The force on the projectile increases as the gradient of the square of the magnetic field produced by the current in the coil. The strength of the magnetic field, and therefore the gradient, increases with the number of ampere turns. The gradient also changes with the ratio of the length to the diameter of the coil. For maximum acceleration, the current in the coil must be zero by the time the projectile passes the center of the coil. Although the equation for the magnetic field along the axis of the coil is fairly straightforward, the equations of motion of the projectile are too complicated for you to solve in the time available for this project. If you wish, you may try some different coil configurations (long and slender, short and fat). Otherwise, you may use the approximate configuration and dimensions shown in Fig. 1, which have been found to give good results with about five meters of wire.

Secure the two ends of the coil wire to the disks, and solder connecting leads to insure good electrical connections to the coil. Connections made with alligator clips to 26 gauge wire often are unsatisfactory because the contact resistance is too high. All the

materials necessary for construction of the coil are available for purchase in the electrical engineering stockroom.
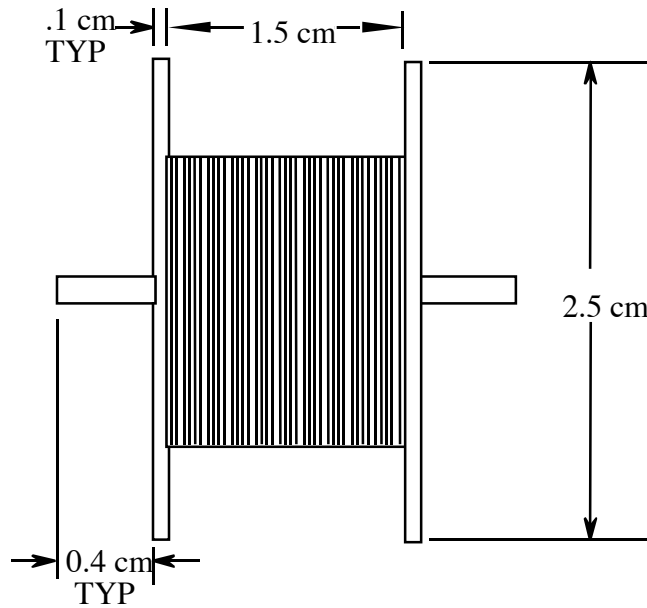

Fig. 1. Configuration of the coil.

2.2   Component value measurement.   Measure the inductance and series resistance of the coil.   For use in the circuit of Section 5, procure the following:

1   100 mH inductor

1   30 nF capacitor (C_1)

1   10 nF capacitor (C_2)

1   300 Ω resistor (R_1)

1   10 kΩ resistor (R_2)

1   5.1 kΩ resistor (R_3)

Measure the values of these components and record them for use in the analysis of Section 5.

3. Analysis of Launcher Circuit

Analyze the launcher circuit shown in Fig. 2 by two methods (classical time-domain solution, and MATLAB ode solver) and compare the results.

3.1   Classical time-domain solution. Write the second-order differential equation for the current i , determine the appropriate initial conditions, solve the equation, and use MATLAB to plot i versus time for $C = 2,000$ μF and for $C = 2,000$ nF, using the values of L and R_s that you measured for your coil.
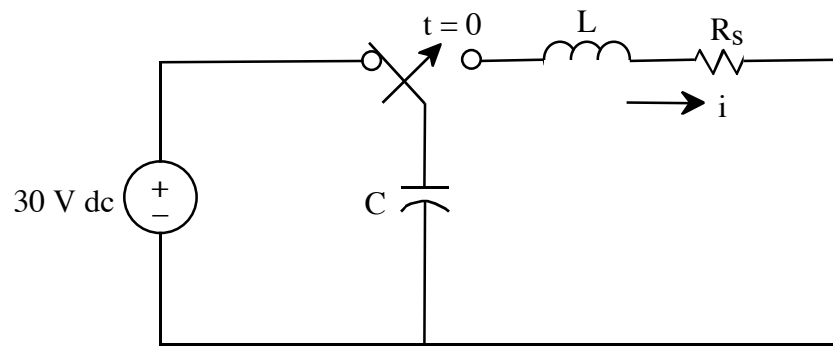

Fig. 2. Circuit diagram for the EM launcher.

3.2 MATLAB ode solver. Write two coupled first-order differential equations for the state variables (voltage across the capacitance and current through the inductance) for the circuit of Fig. 2, and determine the initial conditions for the state variables. Write a MATLAB program using the ode45 function to solve the differential equations and plot i versus time for $C = 2,000$ μF and for $C = 2,000$ nF, using the values of L and R_s that you measured for your coil.

3.3 Comparison and explanation. Compare results of the two methods in two graphs. On the first graph, for C = 2,000 μF, plot i versus time as calculated by each method on the same set of axes. On the second graph, do the same, but with C = 2,000 nF. Explain why the waveform of i for C = 2,000 μF is so different from the waveform for C = 2,000 nF.

4. Construction and Testing of the Launcher

Construct the launcher by connecting the coil and other components shown in the circuit of Fig. 2. For the projectile, use a 3 to 4-mm length of wire cut from a standard paper clip. Be sure to connect the electrolytic capacitors with the proper polarity. Launch the projectile by discharging the capacitor across the coil. Record the distances for three launchings.

Explain how the launcher works, including the need for a short current pulse.

5. Third-Order System

5.1 Analysis. Write three coupled first-order differential equations for the state variables (v_1, v_2, and i) of the circuit of Fig. 3, and determine the initial conditions for the state variables. Assume that the generator voltage is a step function that changes from -v_0 to v_0 at t = 0. Write a MATLAB program using the ode45 function to solve the differential equations and plot v_2 versus time for the component values you measured (Section 2.2; use a 100 mH inductance for this circuit).

5.2 Measurements. Measure and record v_2 for the circuit of Fig. 3 with the components you procured earlier (Section 2.2). Use the function generator rectangular waveform with a low enough repetition rate that the generator voltage approximates the model described in the previous section.

5.3 Comparison. Compare calculated and measured values of v_2 by plotting them on the same set of axes. Give reasons for differences.
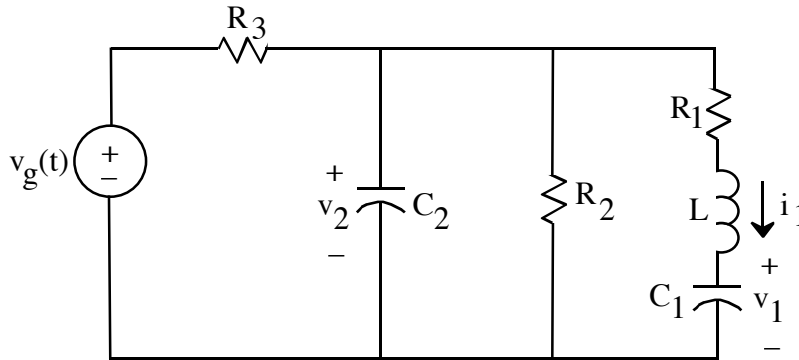

Fig. 3. Circuit diagram of the third-order system.

6. Formal Report

Write a formal report describing your work on this project. See instructions in "Course Procedures" about how to write the report. Include at least the following in your report:

1. A short introduction. You may attach this handout to the report and refer to it so that you don't have to copy the information in it.

2. A careful description of the work that you did in Sections 2 through 5 above.

   a. Give clear derivations of the mathematical expressions. Include consistency checks.

   b. Explain all measurements carefully and include data appropriately in clearly labeled tables (some of them might be placed in appendices).

   c. Include a listing and explanation (may be in the form of comment statements) of computer programs in an appendix.

   e. Give a clear comparison of measured and calculated values by plotting calculated and measured values on the same set of axes (see Section 5.3). Explain why calculated and measured values are not the same.

3. Conclusions, including:

   a. A discussion of the validity of the models used for the devices.

   b. A discussion of the effectiveness of your procedures for analyzing and designing pulse circuits.

J. Your Grade

Your report will be graded according to the following:

Category	Points
Communications	30
2. System Components	10
3. Analysis of Launcher Circuit	20
4. Construction and Testing of Launcher	10
5. Third-Order System	25
Conclusions	5
Total	100