A Coilgun-Based Plate Launch System

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Abstract—**The characteristics and performance of a system for launching metal plates, based on a subscale prototype of a magnetic induction gun, are described. This system is meant to augment the armor of a combat vehicle, by allowing for the interception and disruption of incoming rounds before they strike. Electromagnetic launch is being considered as an alternative to explosive launch because it has several advantages: it causes no damage to the platform, does not require a special logistics train, allows for novel launch geometries, and ties in well with the concept of an all-electric vehicle. The launcher is similar to one previously reported, however significant changes have been made in both its design and its power supply design. A brief history of the evolution of launcher designs at the U.S. Army Research Laboratory is included and key design issues, as identified by both experimentation and theoretical modeling, are presented.**

I. Introduction

While much of DoD interest in electromagnetic (EM) launch research stems from a desire to find alternatives for conventional guns on armored vehicles, electromagnetic launch also has applications elsewhere on the vehicle. As a case in point, the U.S. Army Research Laboratory has a program looking into the possibility of using an EM launch system to augment the armor system of the vehicle [1,2]. As currently envisioned, this system would intercept an incoming round with an EM-launched countermunition, which would at least partially defeat the threat before it strikes the vehicle. One payoff of such a device would be the ability to reduce the amount of passive armor required, thereby greatly reducing the overall weight of the vehicle.

Several different such schemes are being studied at the U.S. Army Research Laboratory (ARL), each with its own defeat mechanism. Most schemes rely on momentum transfer to reduce the round's ability to penetrate the backup armor (e.g. a metal plate is flung at the round, disrupting it and dispersing its effects over some area of the backup armor). For launching the effector, most schemes rely on the traditional method for getting objects moving quickly, by using explosives. In this paper, we summarize ARL's exploration of its one non-explosive option for launching the effector: EM launch. EM launch alleviates some of the disadvantages associated with explosive launch, including the need for a separate logistics train to handle the explosive components. The problem of logistics, while never a trivial one, is of particular concern in modern warfare due to the fact that armored forces may move many hundreds of miles in a day and yet still require refueling and re-supply every few hours. Improved logistics is one of the prime motivations behind the concept of an all-electric combat vehicle (AECV) [2], in which all systems, including the main armament, are powered by a central motor-generator. Such a vehicle might only require diesel fuel and projectiles for operation, clearly simplifying the re-supply process. An EM-based package would be quite consistent with this concept.

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Another possible advantage of EM launch is the ability to launch metal plates in an edge-on orientation, a difficult feat to perform using explosives. A plate launched with its velocity vector parallel to its plane, i.e., in the edge-on orientation, may be more effective at defeating the round. In addition the edge-on orientation may be aerodynamically preferable. The ability of an EM launch system to fire a plate in this orientation may therefore make it an attractive alternative to more conventional explosive launch systems. It also affords the possibility of using electromagnetic forces to *steer* the plate as well as to launch it, which will greatly add to the flexibility of the system.

Magnetic launchers generally rely on the interaction of a large magnetic field and a large electric current present in the projectile. Early in this program it was decided to rely on one of a class of launchers known as a "coilguns," a magnetic induction launcher [3-5]. This differs from a "railgun" style launcher [6] in that the currents in the projectile are not applied directly, but rather are *induced* by a time-varying external field. Induction is the same process by which electrical transformers operate, and in fact the launcher can be thought of as the "primary" coil of a transformer and the projectile itself is the "secondary" coil. This type of launcher is epitomized by the "reconnection gun," investigated by Cowan [3], one version of which demonstrated that high velocities can be achieved by aligning a number of coils along the path of the projectile and firing them sequentially. It successfully launched a 150-g plate at a velocity of 1.0 km/s. The size, weight, and complexity of such a multistage launcher are not suited for an active armor system, however, and therefore only single-stage devices have been considered. With this restriction, the primary difficulty is in containing the necessarily large launch stresses in such a small package.

II. Coilgun Models

Several computer models have been developed at ARL to help identify high performance coil geometries suitable for launching metal plates [1,7-9]. One such model [7] is used to simulate the launch process and derive useful quantities such as the muzzle velocity. It is based on the magnetic launch equation of motion:

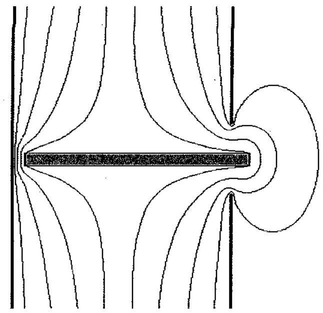

Fig. 1. Side view of a solenoid launcher, demonstrating how a conducting plate distorts the field lines. The plate is launched in the edge-on orientation.

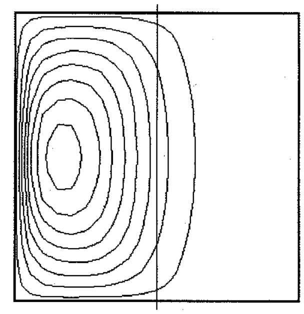

Fig. 2. Calculated shape of eddy current streamlines in a square plate that has halfway exited a launcher (edge-on orientation, viewed from above).

$$F(x,t) = (1/2)I^2(t)\frac{dL(x)}{dx} \quad (1)$$

in which $F(x,t)$ is the force on the plate, x is the plate's position, t is time, I(t) is the current in the launcher coil, and $L(x)$ is the inductance as a function of plate position. The current trace $I(t)$ can be supplied in the form of experimental data or by coupling (1) with the appropriate equations describing the drive circuit. In the laboratory, a capacitor bank powers these launchers, so the equations then resemble those for an *RLC* circuit.

Note that all of the salient information on the magnetic coupling between plate and coil is contained in the inductance gradient function dL/dx. For the purposes of predicting performance it is therefore imperative that this function (or its parent function $L(x)$) be known. For the purposes of identifying likely coil designs, it is convenient to have a means for calculating this for hypothetical geometries. The difficulty in this kind of calculation is in accounting for the eddy currents induced in the plate. At ARL, two separate quasistatic models have been developed in order to predict dL/dx. The first [1,7] mimics the plate with a grid of current filaments, the second [8,9] uses a two-dimensional current sheet for the same purpose. These models also yield useful information concerning fields, current distributions, and the stresses on the plate and launcher. This is illustrated in Fig. 1 which contains a side view of a plate being launched through a slot in the side of a solenoid and demonstrates how a time-varying magnetic field is distorted by the presence of a conducting plate. Figure 2 shows the calculated eddy current distribution for a square plate that has halfway exited a launcher (travelling from left to right), as viewed from above. It should be noted that, while useful for predicting the performance of a particular coil design, these models do not predict the mechanical response of the complete launcher package, which is crucial in determining whether or not the launcher will fail during launch. Codes capable of coupling the necessarily complex and highly dynamic EM calculation to a mechanical response model are not currently available.

III. LAUNCHERS BUILT AT ARL

The following is a brief description of some of the subscale EM plate launchers constructed at ARL. Variations of three basic coil configurations were built, which are referred to as "box coil," "round pancake coil," and "square pancake coil." A "box coil" is simply a solenoid with a square cross-section. The "round pancake" configuration contains two spiral coils, one above and one below the plate, connected by a busbar running down behind the plate. In the "square pancake" configuration square spirals are used. Table I contains pertinent information about the eight launchers built to date, including the metal from which each is constructed, the size of the individual conductor's cross-section, and the approximate mass of the aluminum plate the launcher was designed to launch. Note that some of the launchers were used in range tests where plates were fired against simulated threats traveling at high speed. All launchers were encased in slabs of a fiberglass/epoxy composite, type G10. For a more detailed description of the construction of some of the earlier launchers the reader is referred to ref. [2]. Also included in

TABLE I. LAUNCHERS BUILT AT ARL.

#	Coil Type	Alloy	Conductor Cross Section (mm)	Plate Mass (g)	ΔL (μH)	Notes
1	Box	Al	3x25	200	0.68	Tested different plate materials
2	Box	Cu-Al_2O_3	5x25	200	0.51	Used in range test
3	Round Pancake	Cu	6x13	200	0.64	
4	Box	Cu-Be	13x19	200	0.62	Used in range tests
5	Square Pancake	Cu-Be	6x13	400	1.94	Square cornered spiral
6	Box	Cu-Be	13x19	200	0.62	Same as #4
7	Square Pancake	Cu-Be	6x19	500	1.96	Softer alloy, used in range tests
8	Square Pancake	Cu-Be	6x19	500	2.06	Used in range tests

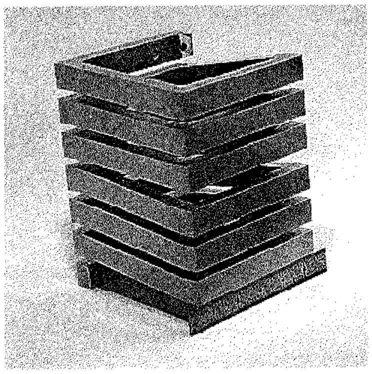

Fig. 3. Box coil geometry used in launchers no.s 4 and 6. The central slot is widened so that a metal plate may be inserted into the coil.

Table I is the measured overall change in inductance ($\Delta L = L(\infty) - L(0)$) for each launcher. This quantity has proven to be a useful indicator of the *relative overall performance* of various launcher designs, in terms of plate momentum achieved for a given set of initial conditions.

Launchers no. 1, 2, 4, and 6 represent a series of increasingly robust box coil designs, culminating in the design used in launchers no. 4 (seen in Fig. 3) and 6. In this design, the coil is machined from a 20.3-cm long 12.7-cm square tube of copper-beryllium alloy (C17200, tensile strength approx. 1500-MPa) with a wall thickness of 1.27 cm. Launcher no. 4 failed, via a crack in a rear corner, while launching a 200-g plate at a speed of 288 m/s.

Launcher no. 5 was the first attempt at a square pancake design, a configuration that simulation indicated would have superior performance. The two 4½-turn, 15.2-cm square spirals were cut from 1.27-cm thick copper-beryllium plate (alloy C17200) and were connected at a rear corner by a short busbar. Figure 4 illustrates the construction of the G10 containment. This launcher failed while launching a 400-g plate at 200 m/s. A postmortem showed that a crack formed at the same location in both coils, at a rear corner, in an intermediate winding, on the side closest to the busbar. This is consistent with modeling in that stresses were predicted to be concentrated at these corners, however it is not entirely clear why the equivalent corner on the side opposite the busbar did not also fail. It is hypothesized that the corners on the busbar side failed first because the slot in the G10 layers, necessary to accommodate the busbar, weakened the structure on that side. This experience lead to the abandonment of square corners and this busbar scheme.

Figure 5 shows the second generation square pancake design, utilized in launchers no. 7 and 8. The most noticeable changes are the rounded corners and the fact that the 15.2-cm square spirals are now cut from 1.9-cm thick copper-beryllium. Simulation indicates that these changes should result in roughly 25% less ΔL than the previous design. Launcher no. 7 also used a softer alloy (C17510, tensile strength approximately 900 MPa) that has almost twice the conductivity of the previous alloy, thus aiding energy efficiency. Launcher no. 8 used the harder alloy. Other changes include an additional ½-turn in each spiral and a

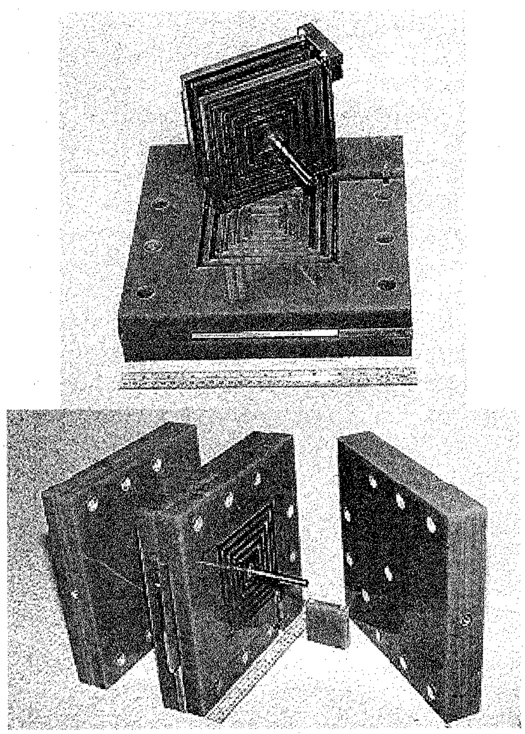

Fig. 4. Square pancake coil and fiberglass containment used in launcher no. 5. Note the aluminum plate partially inserted into the bore.

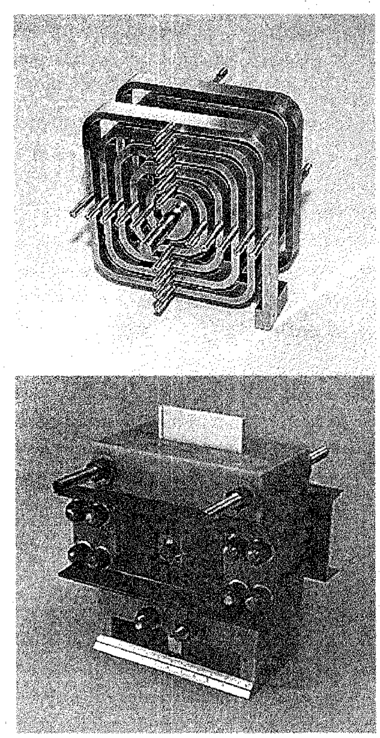

Fig. 5. Square pancake coil used in launcher no. 7 and the completed launcher. Steel U-beams were used to stiffen the outer structure.

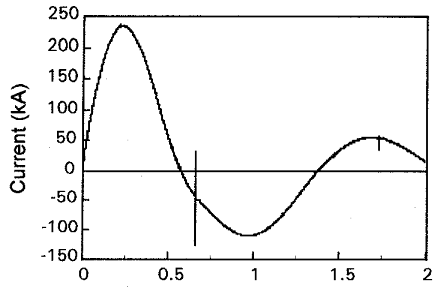

Fig. 6. Typical current trace for launcher no. 7, when launching a 500-g aluminum plate at 280 m/s. The plate leaves the active region of the launcher near the end of the first half-cycle.

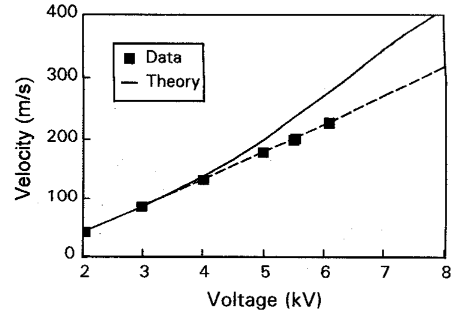

Fig. 8. Plate velocity as a function of initial charge, for launcher no. 7. Reasons for the disagreement between predicted and actual performance are discussed in the text.

busbar that runs part way towards the other side, bends behind the plate, and then continues to the other spiral. Simulation indicates that these two changes should just about recoup the 25% loss in ΔL, and in fact launchers no. 5 and 7 have nearly identical ΔL's. Also seen in Figure 5 are the 6-mm threaded studs added in order to better tie the spirals into the outer slabs of G10. Perhaps the most significant change in the system as a whole was the acquisition of a capacitor bank (8.5 mF, 800 kJ) with over 4 times the capacitance of the supply used with launcher no. 5 (2.0 mF, 400 kJ). This stretches out the current pulses, reducing peak currents by roughly 20% for a given set of conditions. Since stresses vary as the current *squared*, they are reduced by roughly 40%.

Figure 6 contains a typical current trace for these launchers, when powered by the new capacitor bank. It resembles a decaying sinusoid, with a frequency of about 700 Hz, except that the first half-cycle is distorted due to the passage of the plate through the launcher. The launcher inductance changes from roughly 3 to 5 μH during this time. At this frequency, the skin depths for the materials the copper and aluminum alloys used are typically 1-2 mm [10]. The inductance gradient of launcher no. 7 is shown in Fig. 7 (the solid line is a guide for the eye). While they depend on the particular cabling configuration used, the parasitic system inductance is typically on the order of 1 μH and the total resistance of the circuit is typically 9-12 mΩ.

Unlike previous designs, launchers no. 5, 7, and 8 have demonstrated a tendency to deviate from the behavior predicted by the launch model based on (1). Figure 8

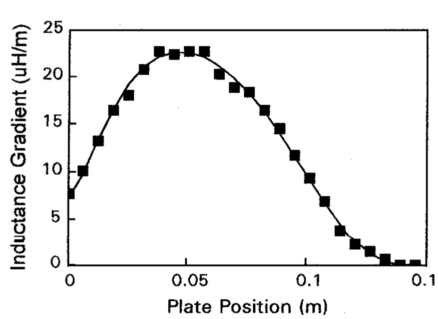

Fig. 7. Inductance gradient as a function of position, for launcher no. 7.

demonstrates how the predicted plate velocities for various initial voltages differ from the measured values, for a 412-g plate (the solid line indicates theory, the dashed line represents the data trend). This is unfortunate in the sense that higher peak currents must be applied to achieve a particular velocity than originally thought necessary. Launch velocities are still quite repeatable, however. A further complication was the evidence of plate failure at velocities above 230 m/s, requiring replacement of the 0.6-cm thick plates (alloy 7075-T651) with plates having a 3.8-cm wide, 1.3-cm thick reinforced rear edge. This increase in mass also requires the use of higher peak currents than originally anticipated. Nonetheless, both launchers no. 7 and 8 were successfully utilized to intercept simulated threats, using 500-g plates traveling at 280 m/s. It is likely that this design is capable of plate velocities over 300 m/s, however it was decided to limit the plate velocities to 280 m/s in order to prolong the life of the launchers.

One possible explanation for this "velocity deficit" is that sections of the coil structure are deforming during launch, to a point where the statically measured dL/dx function is no longer valid. While modeling actual coil deformations is not currently possible, an attempt was made to use modeling to gauge the *severity* of deformation required. As an increase in the separation between the two coils is known to cause a large decrease in dL/dx, this type of "motion" was chosen as a representative case. The results of this study indicated that the two coils would have to (at some point in the launch process) nearly *double* their separation in order to explain the discrepancy at high velocities. Since it is felt that the launcher is unlikely to survive such an event, an alternate explanation was sought.

A more recent hypothesis concerning the disagreement between theory and experiment is illustrated in Fig. 9. Modeling shows that, while the two coils are repelled outward wherever they overlap the plate, they are attracted toward one another in regions vacated by the plate. The flexibility of the G10 slabs separating the coils from the plate may be such that a substantial inward deformation occurs in this area. The hypothesis is that this deformation is sufficiently severe for its periphery to extend to regions in contact with the plate, thus mechanically "pinching" on the plate and impeding its exit. It is easily seen why the velocity

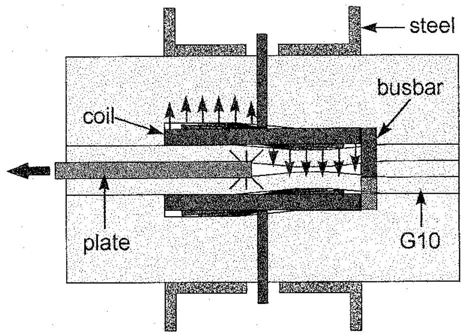

Fig. 9. An illustration of how excessive flexing of the fiberglass composite superstructure might impede the motion of the plate.

deficit would worsen as launcher stresses increase. Tests performed on launcher no. 8 indicated that the nominally 12-mm wide bore narrowed to *at least* 6 mm, at one location, when pulsed with no plate present (albeit a worst case scenario). In addition, plates recovered after high velocity launches show signs of scraping near the center part of their rear edges. Continual flexing of the coil structure could also be the cause of its ultimate failure, due to crack formation and subsequent arcing. It can also so be tied to the occasional unexpected failure of the plates themselves, since it clearly would exacerbate the stresses felt by the plates.

Each of these launchers failed after about twenty-five 280-m/s shots. Since they failed during routine shots, metal fatigue is indicated. A postmortem performed on launcher no. 7 showed that it failed due to the formation of a single crack in the center of straight section of conductor, just behind the central section of a coil. This is consistent with the idea that the rearward sections were flexing heavily at the time of maximum stress, and thus a conflict developed with the more rigidly held central section (the copper-beryllium current feed ties this section to the outer structure). The front sections of the coil would be expected to flex less, as they are pushing outward (against the relatively stiff outer containment) at the moment of highest stress.

IV. Conclusion

Whether or not it is shifting geometry or mechanical interference (or a combination of the two) behind the discrepancy, it currently appears as if the undue flexibility of the G10 superstructure may well be at the root of most problems. Several changes will be made in the next version as a result. Figure 10 illustrates some of the changes. The most obvious change to make is to replace the G10 composite with more rigid varieties: S2-glass/epoxy where an insulating material is absolutely required, and carbon-fiber/epoxy (the darker material in Fig. 10) where it is not. An E-glass/melamine composite ("G9") will be used in non-critical layers. Carbon-fiber/epoxy is preferred because it can be made so that is 10 times stiffer than G10. Noting that the presence of the external steel U-channel stiffeners adds to the inward forces felt by the coils (since they repel the coils just as the plate does), it has also been decided to replace them with carbon-fiber structures. The 6-mm studs will also be discarded, as it is now felt that they failed to restrain the coils, and their mounting holes represent crack formation centers in any event. The coil geometry will remain the same, as this aspect of the design has performed well. In theory, the coils have already demonstrated that they can withstand coil stresses similar to those necessary for the goal of 400 m/s. This is because theory indicates that the 8-kV initial charge, 240-kA peak current pulses used to launch at 280 m/s in the last two launchers *should* be sufficient for near-400-m/s velocities, in the absence of the "velocity deficit" effect.

Simple intuitive arguments and experience suggest that the square-pancake coil geometry is a particularly compact, energy efficient design, and so future launchers will likely represent variations on this theme. The use of more robust composites may allow a less robust conductor structure, and thus open the way for future improvements in energy efficiency. For the purposes of optimization, it is useful to note that the two parameters that most affect the performance of a square-pancake coil launcher are the coil-midplane-to-plate separation and the number of turns in each coil. Since reducing the coil-plate separation would require weakening an already hard-pressed structure, there are no plans to attempt this in the future. However, a 15.2-cm square coil in which seven turns are used, instead of five, is being considered. Modeling indicates that a launcher such as this may have a 50% larger ΔL than the current 5-turn design, though with correspondingly larger internal stresses. It is not

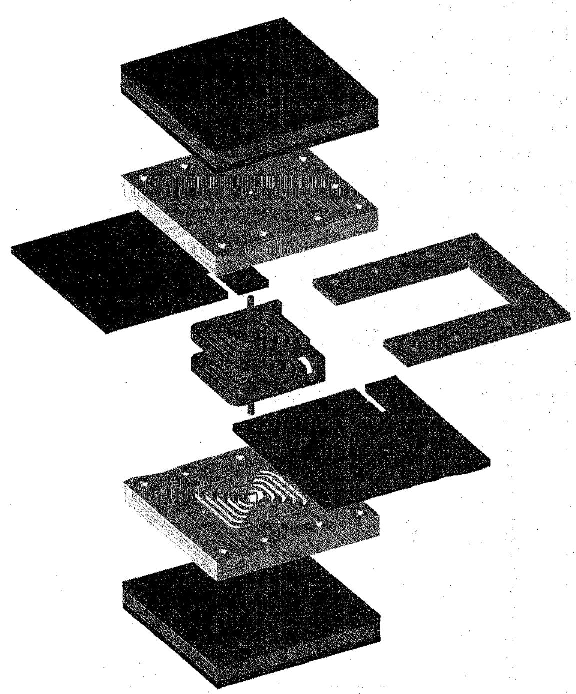

Fig. 10. The next-generation square pancake coil launcher design. The coils are supported by S2-glass/epoxy and carbon-fiber/epoxy slabs. Outer stiffening is supplied by layered carbon-fiber and E-glass composites.

known whether or not the new composite materials are sufficiently stiff and strong to guarantee the survival of such a launcher. An apparent side benefit of added turns is an increase in overall inductance, which stretches out the electrical pulse and thus tends to reduce peak currents (and thus stresses) for a given power supply design. The price that is paid, however, is a longer acceleration time. At some point, this may become too long to meet the requirements of a system meant to fire plates at high-speed projectiles, although the parameters of the power supply can be adjusted to compensate. This will have to be taken into account when a full-scale launcher is designed.

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