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UCRL ID-114847

Transition Armature Technology Project, Progress Report No. 1

R. S. Hawke

June 1 - July 31, 1991

Lawrence
Livermore
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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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ARDEC
Transition Armature Technology Project
Progress Report No. 1
Covering the period June 1 to July 31, 1991

R. S. Hawke
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Executive Summary

This first report covers the period June 1 to July 31, 1991. During this period we developed a detailed project plan which includes a balance between numerical simulation and experimental verification.

A 2D MHD code (CALE) was adapted to a simple solid armature geometry. A numerical simulation verified the magnetic diffusion rate into the armature and rails was being calculated correctly. Furthermore, the distribution of temperature, current density in the rails and armature as well as the interface pressure between the armature and rails were calculated.

A 2D boundary layer code (TKBLIMP) was adapted to simulate the conditions between a solid armature-rail interface as well as a sabot-rail interface. Preliminary results were obtained.

Study of an augmented Quadra-Rail railgun concept was begun. Need for an armature test fixture, launcher test bed and suitable power supplies was established.

The goal of task 4 is to develop advanced launcher concepts. This task will start with but is not limited to multi-rail launchers. The initial consideration of multi-rail launchers is motivated by the increased barrel stress and propulsion force symmetry, separating sabot possibilities and most importantly the possible improved impedance match to pulsed power sources. This task will be accomplished with EM and stress strain numerical simulations, and prototype fabrication and testing.

Project Plan

A detailed project plan was developed and is described in the following sections. It is based on a balance between numerical simulation and experimental verification.

Task 1 - Hybrid Armature

Figure 1 is a block diagram of the planned approach to task 1. The goal of task 1 is to design a high performance hybrid armature and develop scaling relations for bore size, projectile mass and launch velocity.

Hybrid performance has two components, electrical efficiency and mass ratio. High electrical efficiency is achieved by minimizing the rail-to-rail armature voltage which requires minimizing the voltage drop across the plasma brushes. Minimizing the ratio of the hybrid metal link mass required to conduct the armature current relative to the payload mass leads to higher performance. An additional requirement is that the plasma brush must be stably contained between the metal link and rails. Figure 2 illustrates the hybrid armature. Plasma brush confinement requires a yet to be determined minimum length, l_g , in order to provide enough area for the armature current to flow and remain in the metal link as opposed to forming a separate current path through a large rail-to-rail plasma behind the metal link. On the other hand, longer plasma gaps result in larger metal link mass and increase the armature mass fraction. Hence an optimum brush length is desired, just long enough to stably maintain a plasma brush. The required length has not yet been determined nor have the controlling parameters been identified. Quite probably the brush gap, g , and velocity will be amongst the important parameters. The focus of this study is to determine hybrid design parameters. This will be accomplished with a combined numerical simulation and

Detailed Report

Introduction

The goal of the project is to develop an understanding of the physics and engineering limits and design requirements which will lead to 1) high performance solid and hybrid armatures, 2) their use in worn barrels and 3) the design and demonstration of advanced barrel concepts.

The project is divided into 4 tasks: A) design and scaling of high performance hybrid armature/projectile for the 1-4 km/s range, B) determine maximum velocity achievable with solid armature/rail interface, C) develop armatures capable of high performance throughout life of barrel and D) evaluate advanced launcher concepts.

The goal of task 1 is to develop high performance hybrid armatures. Hybrid armature performance is maximized by 1) minimizing the parasitic mass of the solid link and 2) minimizing the plasma brush voltage drop. The solid link mass is minimized by keeping the plasma brush chamber length at a minimum and the crosssectional area needed to conduct the current also at a minimum. Plasma brush stability is essential and sets a limit on the minimum size of chamber required. The requirement will be influenced by several parameters including the gap, velocity and sabot erosion rate. The focus of this task is to determine the limits on hybrid plasma brush design and the controlling parameters. This will be accomplished with numerical simulation and experimental verification.

The goal of task 2 is to develop high performance solid contact armatures. A solid armature requires that the rail-armature contact be maintained throughout the acceleration process from a standing start to high velocities (3-4 km/s). The focus of this task will be to determine what possible fundamental limits on velocity may result from the physics of the sliding interface. This will be accomplished with MHD and boundary layer simulations and experimental tests.

The goal of task 3 is to develop solid and hybrid armatures which will accommodate barrel wear and erosion while maintaining high performance. This will be accomplished by the extension of the approaches used in tasks 1 and 2.

experimental verification effort. The plasma brush will be simulated with CALE, a 2D magneto hydrodynamic (MHD) code. The behavior and stability of the plasma brush will be modeled and used to design critical verification tests.

A sabot is required to support the metal link and to prevent the plasma brushes from simply blowing past the metal link. Initially the sabot is in direct solid contact with the launcher barrel. As the projectile is accelerated to high velocity, friction heats the interface surface leading to sabot melting and vaporization. The melted and vaped sabot, and to a lesser extent, barrel materials will be injected into the plasma brush chamber. The injected mass will mix with the plasma brush material and might play a role in the brush stability and size. In order to estimate the rate of mass injection into the brush, a boundary layer, mass erosion code, TKBLIMP will be used to calculate the rate of melting and vaporization. These results will then be added to the CALE calculations to determine the possible range of effects on brush size, stability and voltage drop. The results of these simulations will be used to design verification tests.

During this reporting period we:

- Developed a numerical simulation plan to study hybrid brush behavior.
- Adapted TKBLIMP to simulate the erosion, melting and vaporization of the frictionally heated sabot-barrel interface.

Task 2 - Solid Armature

Figure 3 is a block diagram of the planned approach to task 2. The goal of task 2 is to determine 1) the physics limits to solid armature function and 2) the optimum engineering parameters that can achieve the maximum velocity. A solid armature is inherently more electrically efficient than a hybrid which has a relatively large voltage drop across the brushes. It is also more difficult to maintain solid electrical contact between the armature and the rails, especially at velocities above 1 km/s.

The solid armature-rail interface can be viewed from a macroscopic and a microscopic perspective. The macroscopic approach treats the interface as a uniform solid metal armature in full contact with a uniform solid rail. As a first step towards simulating the current flow through a rail and a moving armature interface, CALE has been used to

model an armature traveling at 4 km/s (the upper end of the velocity range of interest in this project). Figure 4 shows the contour of the $1/e$ field line which corresponds to the skin depth. The vertical scale is expanded 30 times that of the horizontal scale for clarity. Table 1 summarizes the comparison. Figure 5 shows the calculated temperature profiles at the same time as in Figure 4. Concentrated hot spots form at the corners of the armature as is usually expected. Figure 6 is a plot of the current density flowing through the interface while Figure 7 is a plot of the interface pressure. These figures illustrate the capabilities of CALE which will be used to model a range of operating conditions.

Motion of the solid armature results in frictional heating of the armature and to a lesser extent of the rails. This frictional heating results in surface melting and possibly vaporization. TKBLIMP will be used to simulate this interface and estimate 1) the maximum attainable velocity prior to melting and vaporization as a function of materials and interface pressure and 2) the mass erosion rate throughout the solid, liquid and vapor phases. TKBLIMP combines the effects of elastic material response, surface contact friction, joule heating and surface energy balance to estimate the melting and vaporization transitions as functions of velocity, interface, interface pressure and armature/barrel materials. CALE will also be used to simulate the current diffusion into the armature and rails to establish the joule heating limits of the interface. Joule heating has been added to TKBLIMP in order to simulate the combined heating of the armature.

Preliminary results indicate:

- Joule heating is significant.
- Interface pressure is a significant parameter.
- Failure threshold is set by vaporization, not melting.
- Drastic reduction in sliding friction is modeled as a crest to crest mechanical wear phenomena. The "Point Contact" model advanced by the IAP group has not yet been tested.
- A limitation of between 1 and 2 km/s for solid armatures is emerging from baseline results for FE/FE and Al/Al. A higher threshold may be found for Al/Cu and Cu/Cu.

The microscopic approach is based on the fact that the actual interface of two solids is composed of numerous small contact points rather than perfectly smooth and flat surfaces. Current then actually flows

through the contact points. CALE will be used to simulate a contact point by treating it as a rounded cone in contact with a flat substrate. Barber [1] has published an empirical hypothesis which indicated there is a linear relationship between the force required and the current in order to maintain solid contact. The simulations will test this relationship and either provide insight as to its fundamental basis or place limits on its applicability. In any case, the microscopic simulation will provide a baseline for the macroscopic simulations.

The combined macroscopic and microscopic simulations results will be used to design verification tests.

Task 3 - Worn Barrel Armatures

The goal of this task is to develop both solid and hybrid armatures which will provide high performance over the lifetime of a barrel which experiences wear and erosion. This task is an extension of work described in Tasks 1 and 2 and has not yet begun. Figure 8 is a preliminarily block diagram of the strategy that will be used.

Task 4 - Advanced Launcher Concepts

The goal of this task is to generate and evaluate non-conventional railguns. Initially the focus is on multi-rail geometries. Multi-rail geometries can provide multi-segment sabots which are easier to separate from the payload after launch and might also result in more uniform projectile base loading. Furthermore, multi-rail barrels will experience a more uniform stress distribution resulting in a stronger barrel. Generally multi-rail launchers have lower inductance gradients, hence higher currents are required to maintain a given propulsion force. The addition of augmentation can reverse the need for higher currents.

Figure 9 is a block diagram of the planned evaluation process. First, a 2D code capability to calculate magnetic field and arbitrary current distributions in a self consistent manner will be derived from an existing code. The adapted code will be directly interfaceable to NIKE and DYNA stress-strain codes which are widely used and very suitable for barrel design. This combined capability will provide an effective barrel design capability. The inductance gradients will also be calculated with the adapted code. Those geometries that show favorable inductance gradients will be structurally modeled in order to determine the most suitable materials and estimate the operating

limits. Prototypes of promising designed will be considered for construction and testing.

As a starting point, a Quadra-rail launcher concept has been chosen for analysis. The concept shown in Figure 10, uses 4 primary rails along with 4 augmentation rails to increase the inductance. The inherent symmetry is obvious as is the natural division of the armature into 4 equal segments. If the inductance gradient calculation show promise and a preliminary design bears out the promise a prototype along the lines shown in Figure 11 will be considered.

Discussion

During the course of the first two months of this project it has become apparent that a test bed is needed to perform verification tests. A preliminary search at LLNL has found a few possibilities and will be evaluated in the next reporting period. Meanwhile, the simulation tools are coming on line and are expected to begin providing useful results in the near future.

References

- [1] J. P. Barber, A. Challita, B. Mass, and L. Thurmoood, "Contact Transition in Metal Armatures", IEEE Trans. on MAG-27, (1), January 1991, 228-232.
- [2] F. J. Deadrick, R. S. Hawke and J. K. Scudder, "MAGRAC-A Railgun Simulation Program", IEEE Trans. on MAG-18, (1), January 1982, 94-104.

Table 1

	<u>Diffusion Depth (mm)</u>	
	<u>simulation</u>	<u>analytical</u>
Solid armature (310 μ s)	10	4.0
Rail at 100 mm (25 μ s)	0.86	0.73

Comparison of CALE simulated magnetic diffusion with classical analytical calculations [2]. The lack of perfect agreement between the analytical and simulated diffusion in Al, is due to an incorrect resistivity expression in the CALE simulation. (This will be corrected in later simulations). The results are in sufficient agreement to illustrate the shallow diffusion into a passing rail in contrast to the deep diffusion into the ever present solid armature. The solid Al armature has experienced the full 310 μ s of exposure while the exposure time of the Cu rail depends on the distance behind the armature. The simulation is for a projectile traveling at a constant 4 km/s. Hence a position 100 mm behind the armature has been exposed to magnetic diffusion for 25 μ s.

ARDEC Task 1

Figure 1. Block diagram of approach to Task 1. TKBLIMP, a boundary layer code, will be used to estimate the rate of sabot erosion and material injection into a plasma brush. CALE, a 2D MHD code, will be used to simulate the size, stability and power loss with and without sabot mass injection. These simulations will be used to design hybrid armatures for verification tests. The results will be used to establish scaling parameters.

Figure 2. Schematic section of a generic hybrid armature and sabot. A metal link supported by a sabot along with two plasma brushes forms a hybrid armature. Current flows from one rail across the hybrid and returns in the opposing rail. Magnetic pressure in the plasma brush compresses the plasma. Sufficient chamber length, l_g , is needed to keep the plasma confined in the chamber. Projectile acceleration is provided by the Lorentz force acting on the metal link and plasma brush.

ARDEC Task 2

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Figure 3. Block diagram of approach to Task 2. The solid armature will be simulated as a macroscopic interface between two ideal surfaces and as a set of microscopic point contacts. TKBLIMP and CALE will be used to study the frictional heating, joule heating, current distribution and material phase changes. The simulations will be used to determine the optimum operating parameters to achieve the maximum velocity attainable with a solid armature. Verification tests will be performed as appropriate.

ARDEC Task 3

Figure 8. Block diagram of planned approach to Task 3. Results of parameter variation in tasks 2 and 3 will be used to design and test wear tolerant armatures.

Figure 7. Simulated armature/rail interface pressure profile. The pressure is shown to be smaller in the interface region conducting the current than in the region immediately forward. The pressure drops off linearly as a result of the inertial force decrease.

Figure 5. Simulated Temperature profiles in solid armature and rail.
This snap shot is also for 310 μ s after commencement of current flow through an armature moving at 4 km/s. The highest temperatures are shown to be at the corners of the solid armature as expected.

Figure 4. Snap shot of magnetic diffusion into a solid armature and moving rail. This sample simulation represents the 1/e, skin depth diffusion profile after 310 μ s of diffusion has occurred. The vertical scale is expanded 30 times the horizontal scale in order to show the much smaller diffusion into the "newly" exposed passing rail in contrast the full time exposure the solid armature has experienced.

Figure 6. Simulated armature/rail interface current density profile. The current is shown concentrated towards the back 17 mm of aluminum armature. Simulations of this sort show how much armature is actually needed to commute the current.

ARDEC Task 4

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Figure 9. Block diagram of planned approach to Task 4. Advanced multi-rail barrel concepts will be modeled with TOPAZ EM, a 2D EM code, to first determine the inductance gradients. For those geometries that offer promise, the TOPAZ EM current density and magnetic field distribution results will be used to calculate the surface pressures which will be fed into NIKE and DYNA stress/strain codes to calculate barrel response. These simulations will be used to design full scale and prototype barrels. Were appropriate, prototypes will be built and tested.

Figure 10. Cross section of a full-scale conceptual design of an augmented Quadra-rail launcher. The four rail and multi-rail launchers in general, result in more uniform barrel loads, less distortion, higher operating pressures and the option for natural corresponding four piece separating armatures and sabots. Augmentation is used to supplement the normally low inductance gradient of multi-rail configurations. Both solid and hybrid armatures are compatible with this class of barrel design.

Figure 11. Cross section of a sub-scale prototype augmented Quadra-rail launcher. A standard laboratory approach is shown. Other, more sophisticated approaches are under consideration and will be discussed in the next report.

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