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FRICTION & WEAR UNDER VERY HIGH ELECTROMAGNETIC STRESS

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PROGRAM OVERVIEW

Faculty and staff from the Georgia Institute of Technology, Cornell University, North Carolina State University and Rensselaer Polytechnic Institute are pleased to submit this document, summarizing results of Office of Naval Research (ONR) Grant N00014-04-1-0601, *Friction and Wear under Very High Electromagnetic Stress*. Supported through the Department of Defense (DoD) Multidisciplinary Research Program of the University Research Initiative (MURI), this program was initiated to create, through basic research, design tools and test guidelines for improved railgun performance by advancing the fundamental understanding of the friction, wear and mechanics of interfaces subjected to extreme electromagnetic stress, high relative velocities and elevated temperatures.

Under the direction of Principal Investigator *Steven Danyluk*, research is being addressed by three (3) academic and three (3) research faculty at Georgia Tech, with three (3) additional academic faculty, each representing their respective subgrant institute. During this reporting period, the program accommodated one (1) post-doctoral researcher, six (6) graduate students, and one (1) advanced undergraduate.

Understanding the friction, wear and contact mechanics of a railgun is intimately linked to the metallurgy, chemistry and physics of the sliding surfaces and the transport of electrons through the armature-rail interface. Given that there is little literature available to address these concepts, the team of investigators is looking at a few of the fundamental issues of high-speed sliding under elevated temperatures and extreme electromagnetic stress.

The effort is presently organized as two thrusts: Modeling and Experiment. With respect to the former, investigators are looking at mixed lubrication and its influence on arcing; the contact mechanics of sliding; stress waves; and the atomic mechanisms that initiate surface degradation and regeneration. For the latter thrust, effort has been focused on developing lab-scale tests that can validate the models developed, and investigate material deformation and or melting in a manner that can be scaled to an actual railgun. Lubrication strategies are also being studied, which are intended to promote the successful firing of multiple railgun shots with a goal of substantially enhanced rail life.

During this initial reporting period, the investigators participated in an organizational team meeting at Georgia Tech (April 23, 2004), a Bore-Life & Scaling Workshop in Austin, TX (May 11-13, 2004) and a MURI Kickoff meeting at the Naval Research Lab in Washington, DC (August 12-13, 2004). In addition, the following progress is noted with discussion provided in the next section. This report is an abridged version, edited for public distribution.

I. Modeling:

- Developed a modified Reynolds equation, governing a conducting liquid phase at the armature-rail interface. Began incorporating the equation into a computer code.
- Took initial steps to facilitate the simulation of sliding contact between two hemispherical asperities by means of a three-dimensional finite-element analysis (FEA).
- Evaluated the dependence of parameters on the critical stress wave speed for a railgun structure, based on a Timoshenko beam model with an elastic foundation.
- Simulated the melting of a silver hemispherical asperity due to resistive heating from current flow using the new computer code, ParadyneEM. Magnetic lift-off forces were calculated for current flow through the same hemispherical asperity using the numerical methods incorporated into ParadyneEM. Results compared favorably with those obtained analytically.

II. Experiment

- Performed an initial survey of the thermophysical properties of pertinent railgun interface materials, as well as pertinent heat conduction approximations.
- Performed measurements of viscosity versus temperature for potential interface lubricants of gallium and gallium alloys.
- Initiated steps for the acquisition of a moderate speed (up to 300 m/s), high-current density (up to 10GA/m^2) pin-on-disk tribosimulator from an outside vendor (IAP Research). Initiated the design process for an additional pin-on-disk test apparatus at low speeds (<10 m/s).
- Reviewed the specifications of a high-velocity linear tribosimulator (up to 1 km/sec) that IAP Research has proposed to build for Georgia Tech, so as to expedite tests that provide scientifically, reproducible results. A suite of sensors (e.g., fiber optic strain) will be incorporated to assist in validating the experiments.

Thrust 1
MODELING THE RAIL-ARMATURE INTERFACE

The objective of the modeling effort is to validate observations of the known physical effects in current railgun firings and develop the scaling rules and lubrication schemes to successfully engineer surfaces that enhance railgun performance, reliability and useful life. The following subsections summarize progress in modeling the interfacial phases at the rail-armature contact in concert with the development of contact, stress and atomic-scale models.

1.1 ANALYTICAL MODELING OF INTERFACIAL PHASES IN INTERFACES UNDER VERY HIGH ELECTROMAGNETIC STRESS

Co-investigator: Richard F. Salant (Georgia Tech)
Graduate Student: Lei Wang

MISSION

The objective of this work is an analytical model of the interfacial phases in the rail-armature interface of an electromagnetic railgun, in the form of a computer code and associated documentation. This code would be used in conjunction with codes describing the contact mechanics of the interface, a global thermal model and the electromagnetics of the armature and rail.

BACKGROUND

The goal of an analytical railgun model is to predict the performance of a potential railgun design under given operating conditions and the boundaries of acceptable operation. Since a successful railgun design requires the avoidance of "transition," i.e. arcing across the armature-rail interface, a primary modeling goal is to determine the design parameters and operating conditions necessary to avoid arcing.

The interface conditions between the armature and rail of an electromagnetic railgun can vary with location and time, and depend on a large number of local and global variables. In general, several interface configurations are possible, depending on those variables. They fall into two classes according to whether or not there is mechanical contact between the armature and the rail.

If there is mechanical contact between the armature and the rail, a state of mixed lubrication exists. Although apparent complete mechanical contact exists on the macroscopic scale, on the microscopic scale a "fluid" phase also exists. There will be direct contact between asperities on the armature and those on the rail. Between and around the asperities will be a micron or sub-micron "lubricating film." The phase of this film will depend on local and global conditions. In general, three phases of this film are possible:

i. gas,
ii. plasma,
iii. liquid, if surface wear, melting and/or injection of a conducting liquid occurs.

This is the desired mode of operation of the railgun, since arcing does not occur due to the asperity contact. If there is no mechanical contact, two phases are possible:

i. plasma, in which case there is arcing, and "transition" is said to take place,
ii. liquid, due to either surface wear (accompanied by melting), melt-wave erosion, or injection of a conducting liquid.

The first of these possibilities, plasma, must be avoided, since arcing produces undesirable effects. Therefore if the railgun is to operate with a full film, it is necessary for a conducting liquid to be present.

In general, for a given railgun system, at any instant of time several of these configurations may exist at different locations along the armature, and as time progresses, the configurations may change.

PROGRESS

During the present reporting period, the following progress has been made.

- An extensive literature search has been conducted. As expected, the most relevant papers have been found in the *IEEE Proceedings on Magnetics*. Important papers have also been found in the Russian journal *Technical Physics* (English translation published by the American Institute of Physics).

- Mr. Lei Wang has been hired as a Graduate Research Assistant. Mr. Wang received his B.S. and M.S degrees from Tsinghua University.
- A modified Reynolds equation governing the conducting liquid phase has been developed. The equations governing the conducting liquid are the MHD equations, the classical fluid mechanics equations with the addition of a **J** x **B** term.
- The conducting liquid Reynolds equation, with the flow factors initially set equal to unity, have been put in finite difference form. The Patankar micro-control volume approach was used.
- Work has begun on writing a FORTRAN code based on the above-mentioned finite difference equations.

PLANS

Over the short term, the computer code for the conducting liquid case will be completed and expanded to include the flow factors to account for surface roughness. It will be qualified by comparison with closed form solutions for special cases. It will then be used to perform calculations with parameter values typical of railgun applications.

Following the conducting liquid work, efforts will be directed toward the case of a collision-dominated plasma film. A procedure similar to that used with the liquid will be used. Since the equations are very similar, it is anticipated that the code for the plasma will be similar to that for the conducting liquid.

1.2 ANALYSIS OF THREE-DIMENSIONAL SLIDING CONTACT BETWEEN HEMISPHERICAL ASPERITIES

Co-investigator: Itzhak Green (Georgia Tech)
Graduate Student: Raghvendra Vijaywargiya

MISSION

The sliding of an armature on rails implies that the roughness of both surfaces must be considered in the models of the mechanics. Roughness is typically described as a series of peaks (or asperities) and valleys that interact in contact. The primary objective of this project is to simulate high pressure sliding contact between two elasto-plastic hemispherical asperities by means of a three-dimensional Finite Element Analysis (FEA). This is the initial step in understanding contact between real (rough) surfaces.

BACKGROUND

As discussed by Jackson and Green [1], a 2D quarter circle model representing an asperity coming in contact with a rigid flat (as in an armature-rail contact), was created to improve computational efficiency on the basis of symmetry. Analyses were performed with bottom nodes fully constrained, as well as free to translate in the horizontal direction along the axis of symmetry (See Fig. 1.2.1). This model enables one to:

i. verify that results obtained by a 2D FEA analysis are consistent when the in-plane translation constraints of the nodes are relaxed, versus when all translation degrees of freedom of the same nodes are constrained.
ii. form the basis for a 3D FEA simulation of the sliding contact between two hemispherical elasto-plastic asperities, as experienced at a railgun interface.

PROGRESS

Using the model of Fig. 1.2.1, compression loads were applied via rigid line displacement for the nodes as shown in the figure. The properties of the materials chosen for analysis were similar to steel with an elastic modulus of 200 GPa, Poisson's ratio of 0.32, and yield strength of 1.619 GPa. Using the finite element package ANSYS 7.1™, data were obtained as shown in Table 1.2.1, where, A = area of contact, P = contact force, and ω = interference between the quarter surface and flat. The results indicate that the horizontal translation constraints placed on the nodes lying on the axis of geometric symmetry do not significantly affect the results of the 2D FEA analysis of contact between a quarter circle (asperity) and a rigid plane (flat).

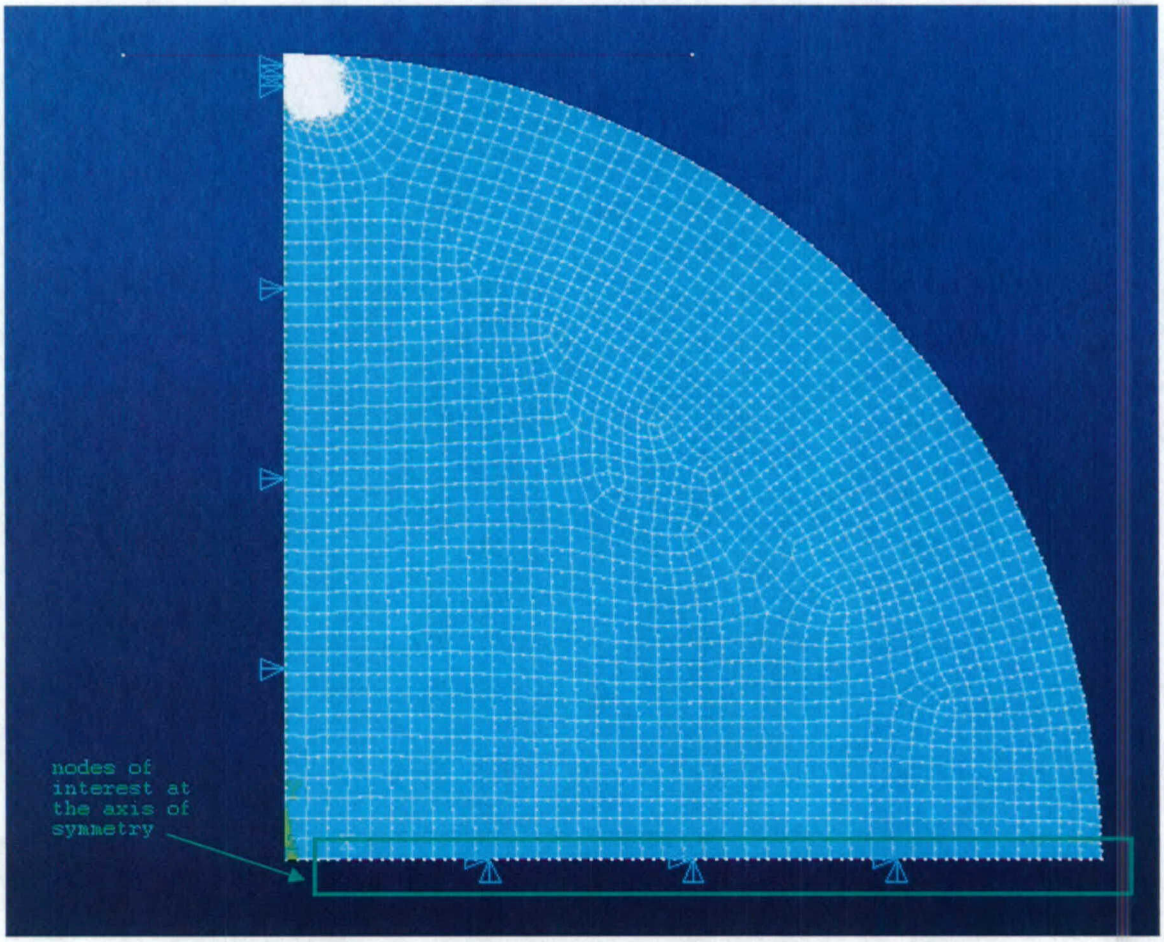

Figure 1.2.1 Axisymmetric nodal constraints in the 2D Quarter Circle Geometry

Table 1.2.1 Comparison of FEA results

Data from [3]				ALL DOF	ALL DOF	UX Free	UY Free	Comparison	
			Applied	Obtained	Obtained	Obtained	Obtained		
ω^*	A^*	P^*	ω (m)	A (m*m)	P (N)	A (m*m)	P (N)	%diff in A	%diff in P
4.51	5.135	8.782	5.0026E-04	1.9372E-03	2.9150E-03	1.9369E-03	2.9094E-03	0.01	0.19
6.76	7.999	15.25	7.4983E-04	3.0390E-03	5.1008E-03	3.0390E-03	5.0891E-03	0.00	0.23
54.09	92.58	212.8	5.9998E-03	3.1790E-02	7.1862E-02	3.1802E-02	7.2486E-02	0.04	0.87
90.15	166.2	391.8	9.9996E-03	5.6630E-02	1.3378E-01	5.6252E-02	1.2972E-01	0.67	3.04
135.23	263.6	623.4	1.5000E-02	8.9188E-02	2.1160E-01	8.9240E-02	2.1143E-01	0.06	0.08
180.31	364.4	853.1	2.0000E-02	1.2263E-01	2.8885E-01	1.2267E-01	2.9161E-01	0.03	0.95
360.61	780.4	1747	4.0000E-02	2.6791E-01	6.0097E-01	2.6765E-01	5.9873E-01	0.10	0.37

During this reporting period, previously documented work associated with this specific contact problem, such as in [2], was researched and the shortcomings, such as the time taken to perform the simulation (about 960 hours, on an average, for each set of results), were noted. The assumptions, theories, and formulations in [1] and [3] form the foundation on which progress has been made thus far.

Since the aim of our simulation is 3D sliding contact, the axisymmetric nature of the problem suggests that the asperities be modeled as semi-hemispheres, and not as quarter circles. Moreover, because a 3D sliding contact involves not only vertical interference but a combination of vertical and horizontal interferences, the assumption that the contact between two rough surfaces be modeled as a rough surface and a rigid flat plane from the Greenwood-Williamson model cannot be used. However, as far as determination of equivalent Young's modulus of elasticity for the two asperities, contact loads, and contact areas is concerned, the Hertzian contact model can form the basis of this study.

Several different approaches can be employed to create an adaptive 3D model that will allow an unrestricted interference simulation between two hemispherical asperities. The most effective method is to reflect a 2D quarter-circle and then resolve the resulting geometries so as to create half hemispheres containing key points at strategic positions to allow for adaptive meshing and contact problem definition. Then, 3D tetrahedral and hexahedral elements can be used to mesh the model, with the mesh generated in the contact region being much denser with significantly larger numbers of elements and nodes to capture the contact phenomena as compared to the coarse mesh for the rest of the bulk volume (See Fig. 1.2.2). A target and contact pair involving the two hemispherical asperities can then be created by using suitable elements from the ANSYS 7.1™ library.

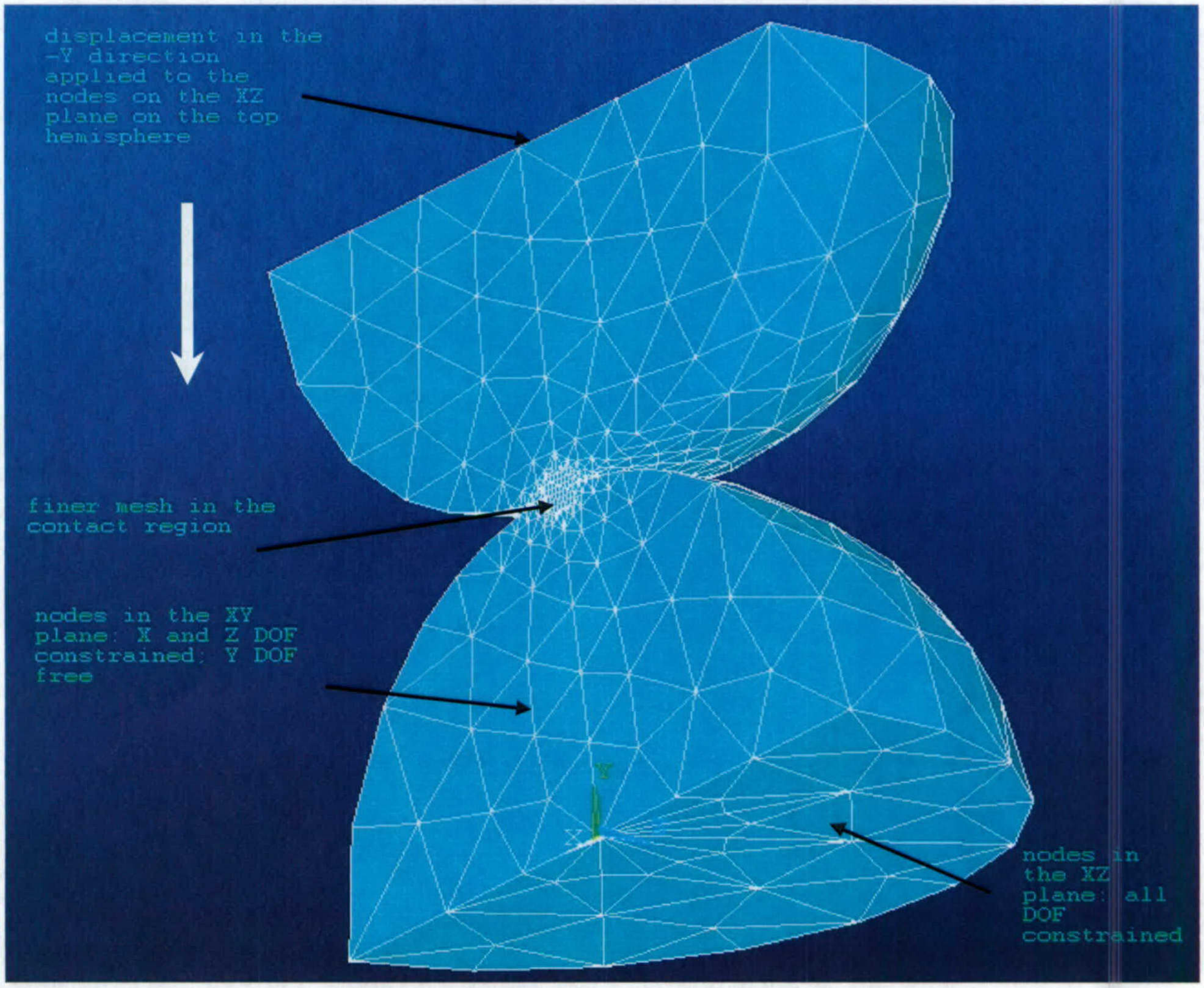

Figure 1.2.2 3D Contact Model Mesh

By definition of the elements used for meshing the 3D contact model, all nodes have a displacement degree of freedom in each of the X, Y, and Z directions. Corresponding to the boundary conditions in [1], the nodes in the XZ plane for the bottom hemisphere are constrained from translation in all directions. By application of symmetric boundary conditions, the nodes on the XY plane for both the hemispheres are restricted from translation in the X and Z directions, but are allowed movement in the Y direction. Nodes forming the elements in the rest of the volumes are allowed all translational degrees of freedom. Application of loads, as well as contact occurrence, is achieved by imparting displacement in the negative Y direction to the nodes forming the symmetric plane on the upper hemisphere.

PLANS

Over the next several quarters, this project will proceed by running the 3D contact model to obtain nodal loads and displacements and simultaneous mesh convergence to optimize meshing. In addition, results will be obtained from the 2D and 3D simulations for this contact problem. We will then simulate sliding contact between the hemispheres once satisfactory results are obtained from the current head-on contact simulation.

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[1] Jackson, R. L., Green, I., 2003, "A Finite Element Study of Elasto-plastic Hemispherical Contact," *Proc. of the 2003 ASME/STLE International Tribology Conference, Preprint 2003-TRIB268.*

[2] Faulkner, A. and Arnell, R. D., 2000, "The development of a finite element model to simulate the sliding interaction between two, three-dimensional, elastoplastic, hemispherical asperities," *Wear 242 (2000) 114-122.*

[3] Jackson, R. L., Green, I., 2004, "A Finite Element Study of Elasto-plastic Hemispherical Contact against a Rigid Flat," *In Print, ASME Transactions, Journal of Tribology.*

1.3 STRESS WAVE DYNAMICS IN ELECTROMAGNETIC LAUNCHERS

Co-investigator: Francis Moon (Cornell University)
Graduate Student: Anthony Johnson

MISSION

One of the goals of this research is to examine the role of stress waves on tribological contact mechanics of a slider magnetically driven along a parallel rail elastic guideway as well as to assess the effect of slider-rail dynamics on electric contact properties.

BACKGROUND

The defining metric in this problem is the critical wave speed related to the shear wave or Rayleigh wave in the rail-support system, which is on the order of 2 km/s. An accelerating slider at low speeds will generate dynamic stresses that will move ahead of the slider, reflect at the rail end and return and interact with the slider. When the slider moves faster than the critical wave speed, most of the dynamic energy will remain with or behind the slider. A particularly interesting case is the transition regime when the slider speed goes through the critical speed.

PROGRESS

The results of several dynamic simulations using a finite element code are shown in Figures 1.3.1 and 1.3.2. Figure 1.3.1 shows the deflection in the rail at three different times for a moving load in a 10 meter rail with a terminal velocity less than the critical wave velocity. The figure shows the wave nature of the dynamics as well as the dispersion of the waves for different wavelengths.

Figure 1.3.2 shows the deflection under the moving load for three accelerations for terminal speeds less than, equal to and greater than the critical wave velocity. Here one can see a significantly different deflection pattern for the trans- and super-critical speeds than the subsonic load speed case. This suggests that there could be a change in the contact pressure under a moving slider as it goes through the critical speed associated with the rail wave speed.

Figure 1.3.3 shows the two wave dispersion modes in a Timoshenko beam on an elastic foundation. These curves are group wave velocities for different wavelengths in the beam. It illustrates the complex wave mechanics that can occur in rail structures when shear deformations are included in the model.

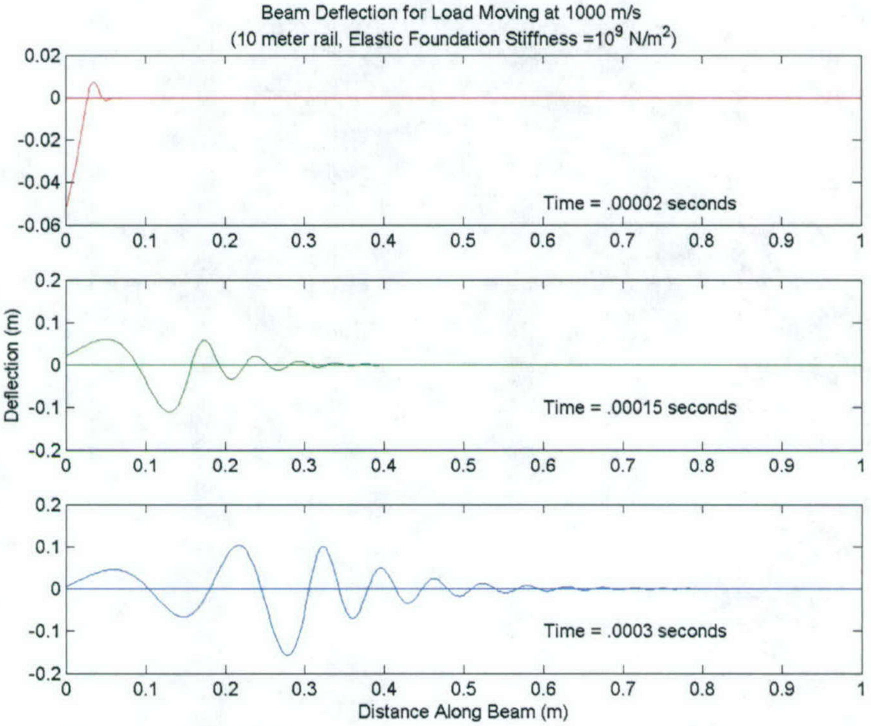


Figure 1.3.1 Wave propagation in a rail with a moving load.

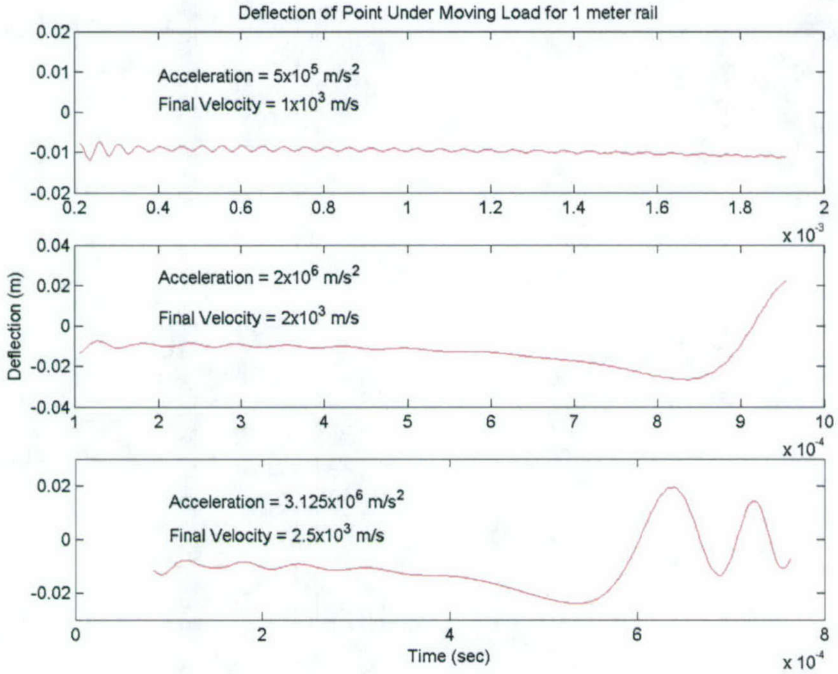


Figure 1.3.2 Deflection under a moving load for (3) different load accelerations in a one meter rail.

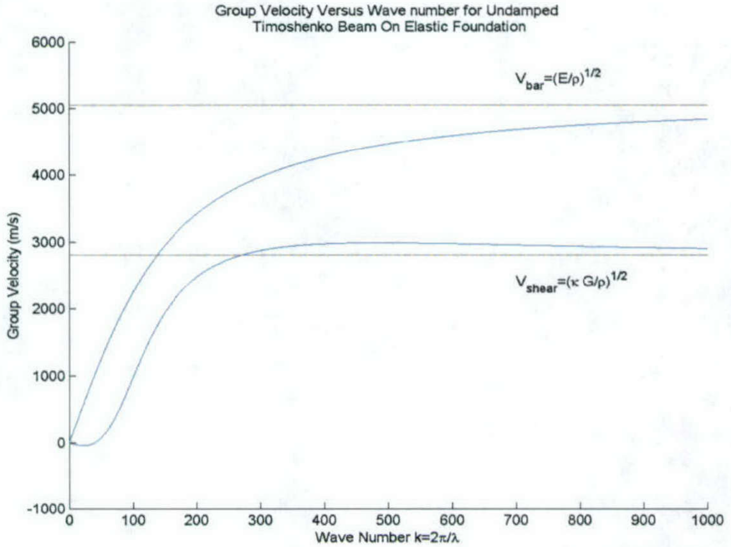


Figure 1.3.3 Wave group velocity versus inverse wavelength for a composite beam and elastic support structure using a Timoshenko Beam model.

PLANS

In these calculations, a moving concentrated load was prescribed. We are now extending these calculations to a moving step load that is more characteristic of the magnetic rail problem. In the next phase of our work, we will try to add the momentum of the moving slider in order to assess the effect of wave dynamics on the contact pressure. Our ultimate goal is to evaluate the dynamic change in contact pressure and its effects on tribological properties as well as the contact resistance as a function of slider speed, rail stiffness and rail length. We are also beginning to design an experiment to measure the effect of wave phenomena in elastic rails on the contact resistance.

1.4 ATOMIC/MICRO-LEVEL MODELING

Co-investigator: Donald W. Brenner (North Carolina State University)
Postdoctoral Fellow: Clifford W. Padgett

MISSION

The sliding of an armature on the rails will eventually need micro-level models since current and heat are transmitted through atomic-scale interfaces. As a consequence, this project seeks to i) develop multiscale atomistic molecular dynamics/continuum simulation methodologies that incorporate the effects of electromagnetic fields and current flow on the dynamics of sliding interfaces, including Joule heating and melting, thermal transfer, and microstructure evolution; and ii) apply our unique methodologies to understand the origin of friction and wear at the rail-armature interface, and from this understanding predict new materials and microstructures that would reduce wear for sliding under high electromagnetic stress.

BACKGROUND

Developing a firm understanding of the origins of the tribological properties of conducting contacts under high electromagnetic stress is critical to the design of new materials with enhanced wear resistance. Due to the high sliding speeds and currents used in railguns, experiments that probe friction and wear processes during sliding are extremely difficult and costly. As a complementary approach to experiment, we are developing and applying new simulation methodologies that allow us to model these processes with atomic resolution. The goal of the modeling studies is to both understand the fundamental origins of the sliding properties of existing materials by comparing simulation results to experiment, and to explore in a cost effective and efficient manner possible new materials and microstructures. Methods that couple high electromagnetic fields with large-scale atomistic simulations have not been previously developed, and therefore much of the work during this time period involved developing and testing a new modeling methodology and associated computer code.

PROGRESS

A new multiscale scheme that couples numerical solutions to continuum heat flow/electromagnetic field equations to atomic trajectories has been developed and incorporated into a parallel molecular dynamics code that uses embedded atom method interatomic forces. The molecular dynamics simulation code, which is called Paradyn, was developed originally by Plimpton and co-workers at Sandia National Laboratory. Our new version of this code, which we called ParadynEM, has a finite difference grid (FDG) overlaid on top of the atoms. This grid serves several purposes. First, the temperatures of the atoms are coupled during a simulation to a numerical solution of the continuum heat equation on the FDG. The experimental thermal diffusivity is used in the continuum calculations, producing an effective heat transport rate that is characteristic of metals without the need to explicitly include electronic degrees of freedom in the interatomic forces. Second, the FDG is used to incorporate heat production into the atomic simulation due to current flow. The resistance in each region of the FDG is calculated from the experimental resistivity and the atomic density in that region. Using these resistances, a network of resistors is established where each FDG region is connected to the surrounding regions by resistors that have properties that are the average of the two grid regions connected by the resistor. Using this resistive network and an applied voltage the potential at every FD point is calculated. The potential difference between connected FDG regions and the resistance are then used to calculate the current between the two points, and the heat resulting from that current flow is calculated and added to the atomic velocities in the appropriate grid region. Finally, using the current at each FD grid region, the magnetic force between grid regions is calculated and added to the interatomic forces from the embedded atom methods potentials. This allows magnetic lift-off effects to be coupled directly into the molecular dynamics simulation.

Illustrated in Figure 1.4.1 is a test case used to evaluate this methodology. The atomistic simulation is composed of a hemispherical asperity with a radius of 20A that contains ~2,500 silver atoms contacting a silver surface containing ~25,000 atoms. Periodic boundaries are used in the two directions perpendicular to the asperity. Test cases were run in which the number of FDG regions varied from 27 to 24025. A voltage is applied from the top of the asperity to the bottom of the substrate, and the calculation is carried out as described above.

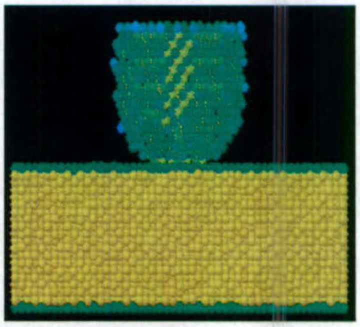
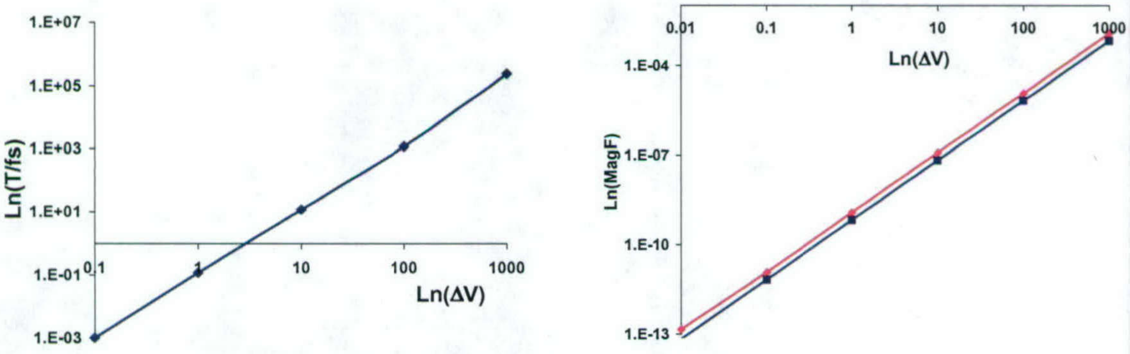


Figure 1.4.1
Schematic diagram of the atomistic simulation.

Plotted in the left figure of Figure 1.4.2 is the natural log of the increase in temperature per femtosecond of the system as a function of the natural log of the applied voltage. The current is very large for this contact area and the rate of temperature increase is correspondingly large, leading to rapid Joule heating and melting. Plotted in the right figure as the squares/blue line is the natural log of the magnetic lift-off force due to current flowing through the tapered asperity as calculated by ParadynEM as a function of the natural log of the voltage drop across the system. Indicated by the diamonds/red line is the log of magnetic force as given by the continuum analytic equation. Our numerical calculations reproduce the analytic result for a hemispherical contact, with the small difference between the two results being due to the finite size of the grid regions.



(a) **(b)**

Figure 1.4.2 (a) Natural log of the increase in temperature per femtosecond of the system as a function of the natural log of the applied voltage; and (b) natural log of the magnetic lift-off force as a function of the natural log of the voltage drop across the system.

PLANS

Over the next year we will use our code to directly model sliding of aluminum contacts under high electromagnetic stress at sliding speeds that are comparable to the fastest rates in typical rail guns. The effects of Joule heating vs. heating due to friction, melting and the production of liquid contacts and its influence on friction and wear will be characterized. Magnetic liftoff effects will be investigated. Plowing and other plastic damage during sliding will also be explored.

Working with *Prof. Juergen Kreuzer* (Dalhousie University), we will also incorporate field evaporation and atom ionization into our simulation code so that the influence of sputtering and etching due to plasma formation can begin to be addressed at the atomic level. In the longer term we will use our code to explore other materials and systems, including nanocomposites structures, with specific systems to be modeled guided by working closely with MURI experimentalists.

The experimental effort, as described in the following subsections, is designed to gather reliable data for use in controlling the friction and wear that accompanies railgun firing. Strategies for producing the optimal armature-rail contact are being developed as are diagnostic tools to characterize the interface and validate the modeling.

2.1 SOLID LUBRICATION AT THE ARMATURE-RAIL INTERFACE

Co-investigator: Thierry Blanchet (Rensselaer Polytechnic Institute)
Graduate Student: Edin E. Balic

MISSION

To reduce the armature melt wear rate, with the goal of preventing loss of initial mechanical interference and resultant electrodynamic transition, through materials selection for railgun armatures and rails, and their overlaying liners, claddings and lubricating coatings and solid films.

BACKGROUND

In Stefani and Parker's 1999 study of the sliding of aluminum armatures (KJ200) within copper rails carrying current of nearly a mega-ampere reaching speeds of approximately 2km/s, the aluminum contact surfaces are observed to melt at a rate of roughly 0.7mm depth per meter of distance slid along the rails. While such melt wear may have some potential benefits to offer the system, such as maintenance of an electrically conductive sliding interface as well as fluid lubrication, the observed rate of melt wear is excessive. A typical engineering surface with RMS roughness on the order of 0.1μm would only require a fluid film of comparable or slightly greater thickness to fill its 'valleys' and submerse its asperity peaks, enabling the entire apparent area of contact to conduct current while minimizing asperity/asperity contact. However the 0.7mm/m melt wear rate occurring over a contact interface having a length ~25mm along the sliding direction corresponds to a molten film thickness of 28μm, excessive by roughly two orders-of-magnitude. As a result, the initial ~1mm mechanical interference of the armature within the rails is quickly worn away, and as the additional electromagnetic loading of the compliant legs of the C-shaped armature against the rails is then diminished when current is dropped as the armature approaches to the muzzle, conductive contact is lost and a transition to higher contact resistance and voltage, with arcing and erosive damage, results. If armature wear depths can be reduced to a magnitude comparable to the initial mechanical interference, such contact transition may be avoided.

PROGRESS

A solid lubrication approach would provide friction-reducing films on armature and/or rail surfaces in hopes of reducing frictional heating and, in turn, melting. However before turning focus onto such surface films, the selection of the underlying substrates should first be re-evaluated, particularly with regard to thermophysical properties. Interfacial heating is partitioned between the heat of fusion associated with melting and heat conduction into the contacting bodies, thus the more interfacial heat can be conducted away the less melting will occur. In terms of selecting simple heat conduction models that may quickly highlight the important thermophysical properties, for bodies such as the rail 'moving' with respect to the input heat flux the rate of motion relative to the rate of conduction must first be considered via the Peclet number. If the ratio of the product of sliding speed and contact half-length to twice the thermal diffusivity, $Pe = Vb/(2\kappa)$, is greater than 10 then high Pe models are considered applicable. Even for a very conductive material such as copper, for b=12.5mm as dictated by a KJ200 armature contact patch, Pe becomes high at speeds of only 0.5m/s, thus high Pe conditions exist along essentially the entire rail length.

In such a high Pe case the amount of conduction into the body that is 'stationary' relative to the contact interface (the armature) is small relative to that into the moving body. Thus the total heat input at the contact interface can be considered as partitioned between conduction into the rail and melting of the armature surface. Therefore, the greater rail conduction can be made through larger products of ΔT_m for the armature and $(k\rho c_p)^{1/2}$ for the rail, the less melt wear will occur. Of course, aspects of the railgun other than thermal must be considered before any materials are substituted.

PLANS

For short-term plans, if melt wear can be achieved through combined ohmic and frictional heating on a benchtop tester, such as discussed in Section 2.3, it is desirable to investigate melt wear rates for potential rail liner materials and armature cladding materials. For long-term plans, it is desired to see if the rail/armature material pairs that appear most promising in benchtop tests provide corresponding changes in behavior on an actual railgun when employed as liners and claddings. Of course such proposed material pairs must also resist gouging, thus it is additionally desired to see if the copper gouging behavior against aluminum observed in railguns can be produced in benchtop tests so that alternate material pairs proposed for thermal reasons can also be screened based upon gouging. Finally, it is desired to better comprehend the fraction of total heat input at the contact interface that results from friction as opposed to electrical resistance, to more clearly gauge the extent to which that total interfacial heat may be reduced through implementation of solid lubricant films or coatings.

2.2 RAILGUN LUBRICATION STRATEGIES

Co-investigator: Scott Bair (Georgia Tech)
Undergraduate Student: David Icenogle

MISSION

This project is experimental in nature and will eventually investigate lubrication strategies for the armature-rail interface, including liquid metal hydrodynamic lubrication and solid lubrication by sacrificial brush.

BACKGROUND

This project experimentally investigates the lubrication of the armature-rail interface by conductive liquids or sacrifical conductive solids. Full film lubrication in conventional machines offers solid-contact free operation and unlimited life. If an electrically conductive full film can be generated at the armature-rail interface, the improvement in reliability is obvious.

PROGRESS

The hydrodynamic approach to minimizing friction and wear at the armature-rail interface can be modeled analytically. Therefore, cooperation with the modeling project of *Richard Salant* (Section 1.1) is underway. A railgun at IAP, Dayton, OH, has been identified for use in testing, and armature design parameters have been selected for the modeling effort.

Our measurements show that the viscosities of gallium, gallium-indium, and gallium-indium-tin, vary little with temperature and pressure, in comparison with organic liquids, over a range of temperature to 180°C and pressure to 800 MPa. The low value of approximately 1 mPa·s is perhaps ideal for a high speed sliding bearing.

The toxicity of gallium and alloying agents was found to be low from the current literature. Corrosiveness of gallium toward structural metals, excluding aluminum, seems to be manageable for the short term, while the long-term corrosion appears to be controversial.

PLANS

Over the next reporting period, test armatures for housing the liquid metal lubricants will be designed and manufactured.

2.3 RAILGUN INTERFACE SIMULATION AND SCALING

Co-investigator: Jeffrey Streator (Georgia Tech)
Graduate Students: Dinesh Bansal and Bobby Watkins

MISSION

We seek to develop tribological testing apparatuses and procedures to provide preliminary evaluation of candidate materials and configurations for electromagnetic launchers. The tests will be designed to discover critical relationships among material and operating parameters and to provide necessary data for the mathematical modeling effort associated with the MURI program

BACKGROUND

The challenge to the railgun community is to develop a methodology for improving the performance and life of electromagnetic launchers (EMLs). Meeting this challenge will require and understanding of the tribological phenomenon that occur at the armature rail interface. Issues such as contact pressure, current density, friction force, interface temperature and material removal rate are viewed as critical factors affecting the operation of an EML. In that regard it is of interest to determine the relationships among the various operating parameters to predict how the armature-rail interface will perform.

PROGRESS

Test apparatuses will be developed to help determine relationships between operating parameters and material behavior under extreme sliding conditions. The first test rig (Test Rig A), shown in Figure 2.3.1, will be a moderate-speed (up to 200 m/s), high-current density (up to 10 GA/m^2) pin-on-disk tribosimulator to be acquired from an outside vendor (IAP Research). This pin-on-disk test represents an improved version of a test apparatus that has been used previously for assessment of the viability of certain material combinations for the armature-rail interface [1]. It will have the capability of *in situ* measurement of contact load, friction, wear, and electrical contact resistance under the high-current densities characteristic of the armature-rail interface.

To date, discussions have occurred between the MURI PI (*Prof. Steven Danyluk*) and IAP Research relating to the performance capabilities and operational demands of the test apparatus. Representatives from IAP Research visited Georgia Tech to review candidate locations for housing the tester and to provide recommendations. Pertinent issues raised included the infrastructure required to provide adequate power, safety, ventilation and noise reduction. A quotation from IAP Research for the fabrication of such device has been received.

The second test apparatus (Test Rig B) for which a design has been initiated (see Figure 2.3.2) is envisioned as one that complements the capabilities of Test Rig A. It will be a low speed (< 10 m/s) pin-on-disk apparatus with the capabilities of high current densities (10 GA/m^2). To date, model equations have been identified to assess the interfacial conditions under various operating scenarios. These equations, derived from Hertzian contact analysis [2] are used to design for the contact pressures and current densities representative of an operating railgun.

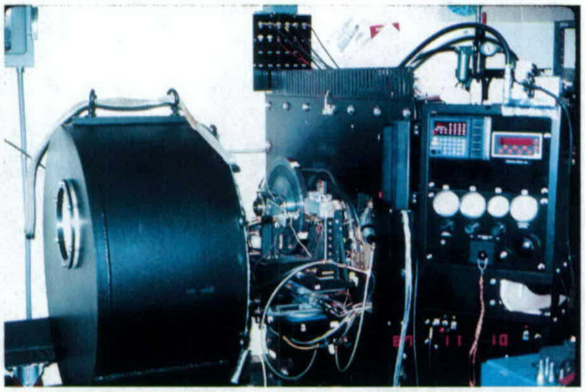


Figure 2.3.1
Moderate Speed Pin-on-Disk (IAP Research)
Tribosimulator Test Rig A

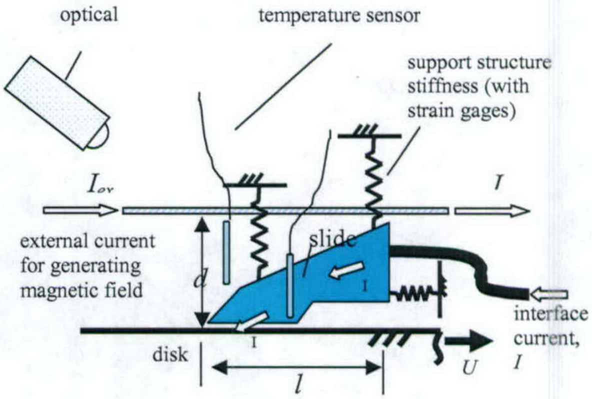


Figure 2.3.2
Schematic of Slow Speed Pin-on-Disk
Tribosimulator Test Rig B

PLANS

Plans for this project include defining the initial testing matrix; completing the design and fabrication of Test Rig B; acquiring and installing Test Rig A; and performing experiments on various materials combinations.

REFERENCES

[1] Bauer, D. P., and Juston, J. M., "Rapid Testing for Multishot Railgun Bore Life," *IEEE Transactions on Magnetics*, vol. 33, no. 1, January 1997, pp. 390-394.
[2] For example: Johnson, K. L., *Contact Mechanics*, Cambridge University Press, Cambridge, 1985.

2.4 DIAGNOSTIC TOOLS

Co-investigator: Gary Gimmestad (Georgia Tech Research Institute)
Research Engineers: Dave Roberts and Jack Wood.

MISSION

Design, develop, deliver, and maintain instrumentation for the Georgia Tech test tribosimulators to enable high-quality measurements of primary data (current, voltage, position, temperature, stress / strain etc.) in high transient magnetic fields.

BACKGROUND

The US Navy requires electromagnetic launchers for shipboard use that are capable of firing thousands of rounds before the launcher rails are replaced or resurfaced. Current launchers (railguns) generally have unacceptable rail wear after only a few launches. Many years of effort at several facilities have not resulted in a clear technology path toward the reliability requirement of the Navy.

There are probably several causes for the current situation, not the least of which is the inherent difficulty of the problem. However, at least one other primary cause is apparent: railgun practitioners sold their technology on the basis of only one parameter: muzzle velocity. The fixation on maximizing muzzle velocity led to a single-shot mentality and a disregard for rail wear. In addition, because many details of the high-current, high-speed sliding contact are not sufficiently understood, the railgun practitioners were forced to adopt a trial-and-error approach to maximize muzzle velocity.

These facts led to the current generation of railguns, which are difficult to use and are instrumented primarily for velocity, along with current and voltage. The armatures are almost always aluminum (to minimize parasitic mass and therefore maximize muzzle velocity) and the rails are mostly aluminum or copper (good electrical conductors). The initial contact pressure is generally undocumented - armatures are simply hammered into the breach. The initial friction forces (static and dynamic) are not measured and cannot be calculated.

The first place to look for a solution to the reliability problem, and the focus of the MURI, is in the tribology of the sliding high-current-density contact. As a part of this effort, an experimental facility is being developed that will include both a pin-on-disk machine and a small rail gun. A pulsed power supply will also be developed for use with either machine. The pin-on disk machine will be used to measure wear rates for different combinations of materials and/or lubricants in controlled static and constant velocity conditions, as well as the contact pressure required to avoid arcing. The force of the pin against the disk and the friction force will be monitored with fiber-optic strain gauges. The pin-on-disk experiments are intended to provide a better understanding of the sliding contact and to lead to candidate materials and/or lubricants for use in a railgun.

The railgun environment is inherently different from the pin-on-disk because of the magnetic forces that press parts of the armature against the rails and accelerate the armature. As discussed in Section 2.3, a railgun tribosimulator will be designed for experiments in controlled, reproducible conditions and for acquiring diagnostic data. The initial contact pressure will be measured, and the force exerted by the armature as it moves through the gun will be measured at several points along the rails with fiber-optic strain gauges. In addition, position, current, and voltage will be monitored. Optical detectors will be used to detect arcing.

The overall goal of the experimental effort is initially to validate the results of the theoretical team's models and ultimately to demonstrate a scale-able solution to the requirements of the Navy. The instrumentation team's mission is to provide the high-quality artifact-free experimental data that will be essential for success.

PROGRESS

The instrumentation team has visited other electromagnetic launcher facilities to determine the current state of the art in their associated instrumentation, and especially to note measurement capability shortfalls and problems. We also participated in the MURI kickoff at NRL, again noting shortfalls in diagnostic data. We have also conducted literature searches to discover the current availability of commercial optical sensors.

Several types of fiber optic sensors are available to measure strain. These sensors are immune to magnetic fields and in addition have the high bandwidth required for measuring transient phenomena that last only milliseconds from start to finish. Fiber-coupled sensors have been developed for measuring current and voltage. Such sensors are partially immune to magnetic fields because their signals, from the gun to the instrumentation room, are transmitted optically. In addition, open path interferometric optical sensors are available to measure position as a function of time (and hence its time derivatives speed and acceleration).

PLANS

The instrumentation team is currently conducting a review of the specifications of the three test instruments that IAP has proposed to develop for our MURI experimental team (power supply, pin-on-disk machine, and high-velocity tribosimulator). We will participate in the design of the instruments to ensure that diagnostic measurement capabilities are built in.

Long-term plans are to develop and maintain a high-quality, artifact-free measurement capability at the Georgia Tech experimental facility, and ultimately to develop advanced instrumentation for railguns that will be employed at other, larger-scale facilities.

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14. ABSTRACT

This document summarizes initial progress toward advancing the fundamental understanding of the friction, wear and mechanics of interfaces subjected to extreme electromagnetic stress, high relative velocities and elevated temperatures. During this reporting period, faculty and staff from Georgia Tech, Cornell, N.C. State and Rensselaer Polytechnic performed tasks in two thrust areas of basic research: Modeling and Experiment. With respect to the former, investigators are looking at mixed lubrication and its influence on arcing; the contact mechanics of sliding; stress waves; and the atomic mechanisms that initiate surface degradation and regeneration. For the latter, lab-scale tests that can validate the models are being developed in a manner that will permit scaling of results to a railgun application. Material deformation/melting attributes are being studied with the development of lubrication strategies to promote the successful firing of multiple railgun shots with substantially enhanced rail life.

15. SUBJECT TERMS

Electromagnetic Launchers; Railguns;
Tribology; Friction; Lubrication; Wear.

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