Abstract

One of the challenges in modeling physical phenomena in electromagnetic launchers is solving coupled electromagnetic and mechanical equations. The electromagnetic fields exert forces on conducting components, which mechanically deform them, thus altering the electromagnetic fields themselves. In some instances, a tightly coupled computational process is required to produce an accurate model of a given problem. However, for certain cases loosely coupled solutions are acceptable if the field quantities do not appreciably change with deformation. The large current densities and relatively small mechanical deformation in electromagnetic launchers lend themselves to a loosely coupled model. In this research, we have analyzed a rail gun experiment to see if such a model accurately reflects physical phenomena.
**Background**

While the basic theory of electromagnetic launchers is simple, there arise numerous complications with physical implementations. Most notably is arcing, or transition, at the armature-rail interface. Determining the complex processes that lead to transition is an important step towards rail gun viability. The necessity to maintain solid electrical contact while simultaneously withstanding extremely high accelerations and velocities gives rise to difficult engineering problems. These difficulties warrant a more accurate understanding of the current flow, temperature distribution, and mechanical deformation in electromagnetic launchers.

Complex interfacial phenomena are exceedingly difficult to measure in-bore during an experiment and post-experiment analysis of the rails and armature is limited in scope. These facts combined with the high cost of electromagnetic guns and the limited number of shots that can be conducted on a regular basis make an accurate computational railgun model desirable. A model can reveal electromagnetic and mechanical effects that could only be measured indirectly, if at all, in an actual experiment.

An ideal electromagnetic computational model would simultaneously solve electromagnetic and mechanical equations to mimic physical dependencies as closely as possible. However, due to the discrete nature of mechanical systems, the mechanical simulations must be solved on a much finer time scale than corresponding electromagnetic models. This favors the development of a loosely coupled model, so that the electromagnetic and mechanical solutions can be solved on different time scales.

**Theory**

This research focuses on a newly proposed armature design in solid to solid contact railguns. A grooved armature and rail pair was constructed such that they would interlock during firing. The interdigital armature concept was proposed to better control electrical current densities at the rail-armature interface. By enmeshing the rail and armature, the nature of the contact area is fundamentally altered.

A few predictions can be made by conceptually analyzing the geometry of the interdigital armature. Electrical current densities should be lessened at the rail-armature
interface due to a greater surface area of contact, but the overall current through the armature should not be fundamentally altered. Therefore, internal current densities within the throat region should closely mimic a standard c-shaped armature. Also, the armature fins pose a danger of premature melting during a launch, since they are relatively thin and heat quickly. An accurate electrothermal model was therefore developed to predict material loss due to melting.

Computational simulation allows these factors to be tested so that oversights can be corrected before experimentation, allowing a higher utilization of resources.

**Computation**

The three dimensional finite element analysis programs DYNA3D and EMAP3D were used to model the railgun experiment. DYNA3D is a mechanical load-based simulation code originally developed at Lawrence Livermore National Laboratory for a wide variety of mechanical problems. EMAP3D is an in-house electromagnetic finite element code, which analyzes both thermal and electromagnetic effects.

![Figure 1: A graphical representation of the current pulse used in all simulations.](image-url)
A model of the armature and a section of rail for the simulation was constructed using MSC Patran. Electromagnetic conditions were specified by assigning a magnetic tangential flux to the surface above the rail gun, and an electric pulse through the breech ends of the rail.

The model was then run through a two millisecond stationary simulation using EMAP3D, with temperature and current density results being recorded every half millisecond. Post-processing and visualization was done using Altair HyperMesh. All calculations were done in quarter symmetry; to substantially reduce the computation time involved. The current pulse used in the simulations is a linear approximation to those found in an actual rail gun (figure 1). The results from EMAP3D provided an analysis of the current flow through the armature and rail during the shot.

The first model constructed possessed full contact between the armature splines and rail.

The EMAP3D results show a high current density on the leading and trailing corners.

Figure 2: Splined Armature on Grooved Rail at 0.5ms. Note the high current densities on the leading and trailing corners.
edges of the armature (figure 2). They also reveal an extremely high current density along the outer surface of the rail and armature during the first half milisecond of the shot, due to the slowness of the permeation of the magnetic field into the metal of the armature and rail. The armature was designed such that the rail does not fully come in contact with the body of the armature, allowing the armature to expand during launch as the armature splines wear away. However, this design had the side effect of severely reducing and dividing the cross sectional current carrying area between the rail and the armature body. However, the temperature distribution did not appear sufficiently high to have melted the armature, except in the throat of the armature (figure 3).

Figure 3: Splined Armature on Grooved Rail Temperature at 2ms. Note the high temperature in the central region and the moderately low temperature at the corners.
A subsequent model was constructed with gaps between the electrical contact on one side of the splines as would be expected in the actual experiment, since the grooves in the rail are wider than the splines on the armature. This correlated well with the first model, with only a slightly modified current distribution.

A model of the interdigital armature on flat copper rail was also constructed. The gaps in the rail-armature interface should allow a faster permeation of the magnetic field through the armature, but at the cost of higher current densities through the splines (figure 4).

A final model was constructed of a standard c-shaped armature on the grooved rail, and yielded similar results to the interdigital armature on flat rail.

DYNA3D was then used on the primary model with gaps in the electrical contact to show deformation of the rail. It showed a clear deformation of the rail by purely electromagnetic forces since the armature remained stationary (figure 5).

Figure 4: Splined Armature on Flat Copper Rail Current Density at 0.5ms. Note the high currents in the armature splines.
Experimentation

The interdigital experiment was carried out on the IAT Medium Caliber Launcher in mid-July 20002. Upon removal of the containment modules there was obvious deformation of the rails. The rail material was a soft and pliable aluminum (Al 6061) used in heat sink applications. It bent easily under the high pinch forces exerted by the magnetic field, most notably at the edges of the rail (see figure 6). These pinches collapsed the ridges of the rail, entrapping the splines of the armature early in the shot, and causing them to be ripped off. The DYNA3D results closely resemble those seen during the actual experiment, validating the use of a loosely coupled simulation.

A similar rail with greater lamina thickness has been proposed, which should withstand the electromagnetic forces to a higher degree. This rail is currently being modeled with the interdigital armature so that results can be obtained before further experimentation is carried out.

Figure 5: DYNA3D results showing deformation of the rail.
Conclusion

A loosely coupled finite element model has been shown to closely correspond with physical experimentation in electromagnetic launchers. Further development of these modeling systems could allow new methods of analysis and allow concepts to be tested before experiments are performed.

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Figure 3: Splined Armature on Flat Copper Rail Current Density at 0.5ms. Note the high currents in the armature splines.

Figure 7: A graphical representation of the current pulse used in all simulations.

Figure 5: DYNA3D results showing deformation of the rail.

Figure 6: A picture of the rail, post-experiment. Note the folding effects and the pieces of splined armature (labeled A-F). The arrow points towards the gun breech.
References
