Electromagnetic Formation Flight

Progress Report: September 2002

Submitted to:	Lt. Col. John Comtois Technical Scientific Officer National Reconnaissance Office
Contract Number:	NRO-000-02-C0387-CLIN0001
MIT WBS Element:	6893087
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1 Introduction

1.1 Description of the Effort

The Massachusetts Institute of Technology Space Systems Lab (MIT SSL) and the Lockheed Martin Advanced Technology Center (ATC) are collaborating to explore the potential for an Electro-Magnetic Formation Flight (EMFF) system applicable to Earth-orbiting satellites flying in close formation.

1.2 Progress Overview

At MIT, work on EMFF has been pursued on two fronts: the MIT conceive, design, implement and operate (CDIO) class, and the MIT SSL research group, as described in the April 2002 progress report.

Recent work in the MIT SSL has focused on trade analyses for the sizing and design of the electromagnets that will be used as actuators in Earth-orbiting EMFF applications. The first trade determines the benefits of using electromagnets with or without ferromagnetic cores. The second analysis optimizes the mission efficiency of a three-spacecraft EMFF cluster configured collinearly. **The following report summarizes these trades and the progress made in the sizing and design of an electromagnetic actuation system for EMFF control.**

2 Coil vs. Core

Before optimizing the system size for EMFF spacecraft, determining the effect of magnetizable cores is the first design step. Spacecraft can be designed with either electromagnetic coils only, or coils wrapped around paramagnetic or ferromagnetic cores. Magnetizable cores can directly improve the electromagnetic attractive force; however, EMFF with cores must account for the additional core mass.

To conduct the following trade analysis, the system masses of a coil-only system and a coil-with-core system are constrained to be equal. The normalized force and acceleration between two axially aligned magnets are then determined. The normalized force has direct impact on a mission baseline, while the acceleration determines spacecraft agility. These aspects of EMFF spacecraft will also be explored later. To model the coil-with-core configuration, the iron core system mass increased with increasing core dimensions while the copper wire length and thickness were held constant. This is a necessary constraint since the wires in a coil have current density and temperature limitations. For the coil-only system, mass was increased with the number of wire turns. Wire length of the coil was increased to keep the system mass equal to that of the core system.

Figures 1 and 2 compare the coil-with-core and the coil-only systems. The trade models two axis-aligned electromagnets and calculates the normalized axial forces and accelerations as a function of core radius, and hence system mass.

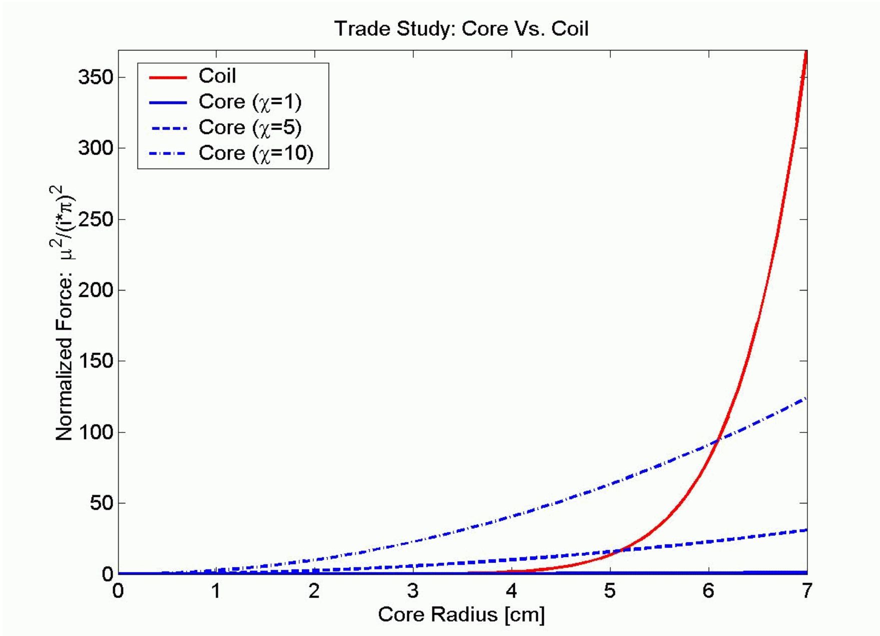

Figure 1. Normalized Forces for Core and Coil Systems

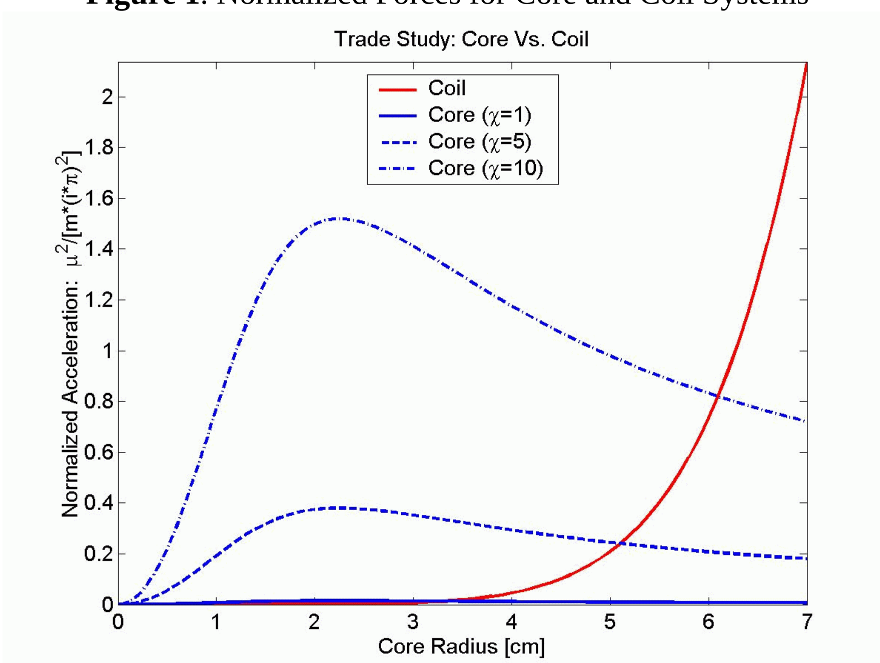

Figure 2. Normalized Accelerations for Core and Coil Systems

There are two useful results from this trade study. For systems with small core or coil radius, mainly testbed-sized vehicles, a core with relatively modest magnetic amplification factor, χ, will greatly improve the system baseline and agility. However, flight-sized EMFF systems will be much larger and will require larger coil and core radii. For these systems, a coil-only configuration is more beneficial, since the normalized force and acceleration for the coil-only system increase dramatically with increasing radius.

3 Three-Spacecraft Sizing

Now that spacecraft have been selected with coils only, we can determine the optimal distribution of EMFF system sizes according to mission efficiency. The model considered consists of three collinear EMFF spacecraft: one center vehicle and two vehicles rotating about the center one. The mission efficiency is measured by the productivity divided by the mission cost. Productivity is proportional to array rotation rate; the faster the array can survey a region, the more data it can collect in a given amount of time. Mission cost is defined as total spacecraft array mass.

The MIT SSL has conducted similar mission efficiency trades for two identical spacecraft. With three spacecraft, the constraint of identical spacecraft masses has been dropped because it will not yield the highest mission efficiency. Since the center spacecraft does not change attitude during array rotation, increasing its mass will not affect the rotation rate. Therefore, the EMFF mass between the two outer spacecraft and the center spacecraft can be redistributed until optimal mission efficiency is achieved. The number of coil turns and coil current can be traded to determine the mission efficiency, J.

As a baseline J, three identical spacecraft with 2000 coil turns and 13 A was used. Figure 3 shows the effect of varying the current as the number of coil turns is kept fixed. Maximum J occurs when the currents are 128 A for the center spacecraft and 68 A for the outer spacecraft. This new configuration yields a mission efficiency 3.8 times greater than the baseline case. The coil currents exceed the limit that copper wires can conduct; however, there is a solution that will be discussed after this final step of system sizing.

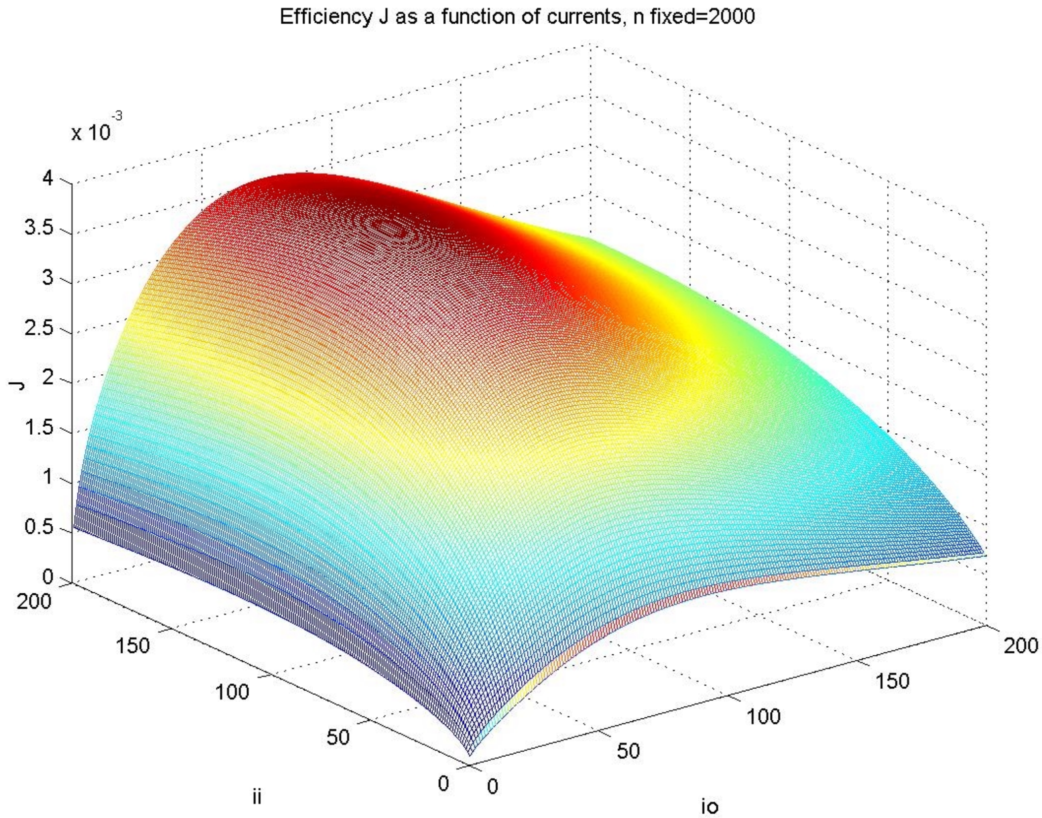

Figure 3. Mission efficiency with varying coil currents

Using these optimal currents, the number of coil turns was varied and the result is shown in Figure 4. The maximum J in this case is 5.4 times greater than before and almost twice as efficient as the baseline case. This final case yields a center spacecraft with 10000 coil turns and outer spacecraft with 8000 coil turns. This point design demonstrates how mass can be redistributed to increase mission efficiency. The MIT SSL is currently working on algorithms for a more generalized result for this multivariable problem.

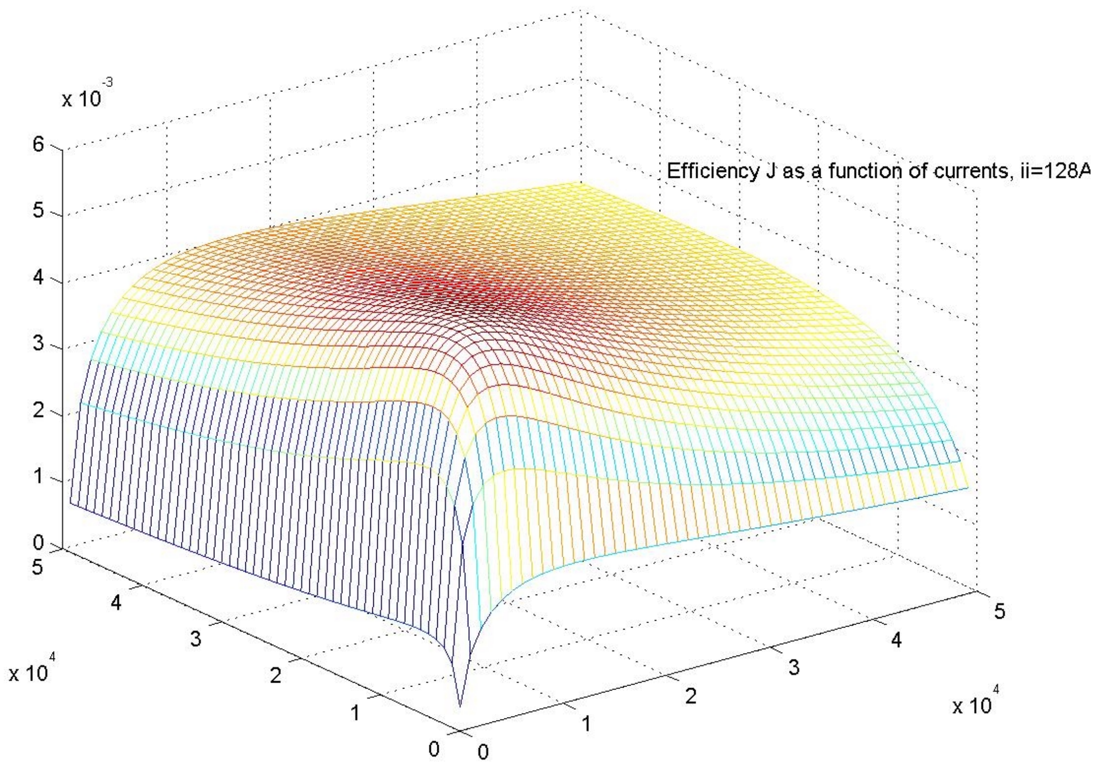

Figure 4. Mission efficiency with varying coil turns

4 Conclusions and Other Work

Earlier, optimizing mission efficiency yielded a case with relatively high currents for normal copper coils. However, these currents are in the range of superconducting coils. The MIT SSL is examining the effects of integrating superconducting coils into EMFF. High-temperature superconducting coils will allow ten times more current and greatly increase the electromagnetic forces. For testbed vehicles, superconducting coils must be cooled with liquid nitrogen, adding to system mass. For flight EMFF systems, some other means of temperature regulation will be used. Therefore superconducting coils have the ability to greatly increase mission efficiency without adding significant costs.

Finally, the MIT SSL and the associated CDIO class are continuing to design and construct vehicles for an EMFF testbed. The class is currently researching the use of superconducting coils and is developing the algorithms necessary to control the testbed.