# Electromagnetic Formation Flight System Design

**Daniel W. Kwon**

**Abstract** Electromagnetic Formation Flight (EMFF) is a proposed method of actuating multiple spacecraft in relative degrees of freedom using electromagnetic forces and reaction wheels. The electromagnetic dipole is created by running current through high temperature superconducting wire. One of the challenges of EMFF is maintaining the cold temperatures necessary for superconducting. The current thermal design uses cryogenic coolers and multilayer insulation. This paper investigates models of the thermal design developed in Matlab and Sinda. The temperature distribution is simulated first using a simplistic 1-D model and then a 3-D model for the coil. The discrete solution procedure involves differencing Laplace's equations and includes the effects of a material with anisotropic thermal conductivity and multiple layers of insulating material. These results are then compared to experimental data, which are conducted using a copper test article in a vacuum chamber. Work done on the Matlab model to match the experimental environment includes modeling the free-molecular flow and accounting for the variation of parameters as a function of temperature. The Matlab model, Sinda and experimental results correlate well ensuring that the EMFF thermal design will operate successful on a satellite.

## 1 Motivation

An increasing number of missions are using multiple spacecraft flying in close proximity to replace traditional large monolithic space systems. Formation flying space interferometers are an example of this application. A method of providing actuation for these formation flight satellites is the use of electromagnetic forces and reactions wheels. This method has several advantages over traditional propellant-based thrusters such as the replacement of consumables to extend mission lifetime, elimination of impinging thruster plumes, and the enabling of high $\Delta V$ formation flight

D.W. Kwon
Massachusetts Institute of Technology, Space Systems Laboratory, Cambridge, Massachusetts 02139, USA
e-mail: dankwon@mit.edu

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missions [1]. A large steerable electromagnetic (EM) dipole can be created by running current through three orthogonal coils made of high temperature superconducting (HTS) wire. The EM dipole creates coupled forces and torques on nearby satellites with electromagnetic formation flight coils. Using a reaction wheel, one can de-couple the forces and torques to provide all the necessary actuation in relative degrees of freedom for a formation flight array [2]. Figure 1 shows a conceptual drawing of a small EMFF satellite which could be used for Earth observation missions.

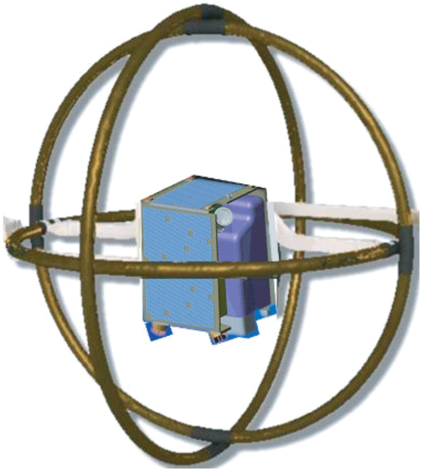


**Fig. 1** Conceptual drawing of a small EMFF satellite

The HTS wire is an enabling technology for EMFF because it allows the creation of a large dipole field. One of the challenges of using HTS is maintaining the temperature necessary for operation. The entire length of the superconducting wire must be maintained below a critical temperature in order for it to operate at superconducting levels. Commercial off-the-shelf (COTS) wire from American Superconductor used by the EMFF testbed has a critical temperature, $Tc$, of 110 K. For EMFF satellites in the proximity of Earth, LEO or GEO, heat from the sun and Earth need to be rejected in order to maintain temperatures below $Tc$. This can be accomplished using cryocoolers and various types of insulation such as Multilayer Insulation (MLI). One characteristic of the HTS wire is that at colder temperatures more current can be driven through the wires creating a larger dipole field and thus improving the performance of EMFF. However, this benefit comes at the expense of additional power and mass required by the thermal system. The unique problem investigated in this research is the topic of cooling large space structures.

The coil thermal system design is critical for the operation of EMFF in space. On the MIT-Space Systems Lab EMFF testbed, the coils are immersed in a bath of liquid nitrogen to maintain a continuous temperature of 77 K [3]. The use of liquid nitrogen on the testbed does not migrate into a flight design because the liquid nitrogen is a consumable. Since one of the benefits of EMFF is to replace consumables the design of the thermal system must be self-sufficient. The first task to accomplish the objective is to model the thermal performance of the design in simulation using

Matlab. Operation of the design or a scaled model in a vacuum chamber, which simulates the space environment, is then used to validate the Matlab models. Once the cooling methods, heat distribution, and heat rejection methods are modeled and experimentally verified, the thermal design can be migrated to a flight version with high confidence.

## 2 Design Overview

The design of the coil thermal system is shown in Fig. 2 for a single coil. The HTS wire stack is wrapped around a thermally conductive jacket, which provides structure for the wire stack and electrical isolation. Around this is MLI, which provides good insulation from the outside environment reducing the heat load into the coil. The thermally conductive jacket also functions to provide a uniform temperature distribution circumferentially around the coil, to serve as an attachment point for cooling, and as structure for the coil system and spacecraft. Heat is extracted from the coil by a cryocooler.

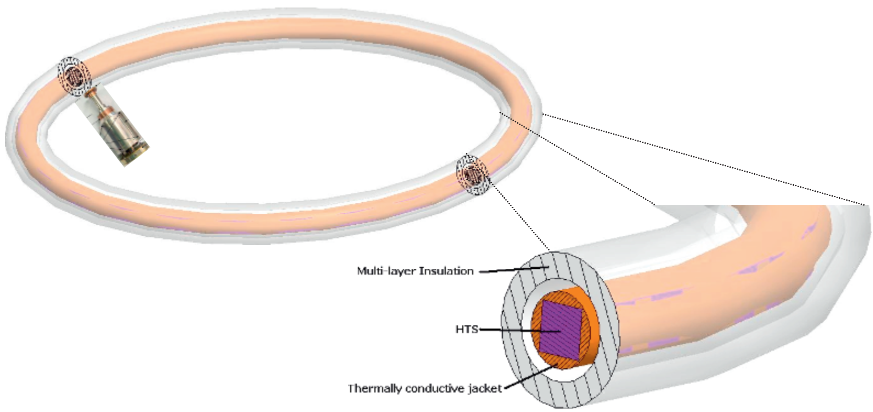



**Fig. 2** Design of an EMFF coil thermal system

System trades have been performed to analyze the cost benefits of operating more than one cryocooler. These analyses assumed steady state bulk heat flow with a uniform temperature and heat flux distribution. It was determined that using multiple cryocoolers operating at different temperatures results in a minimum total power consumption point. This is because a cryocooler requires less power when operating at warmer temperatures, given a constant thermal load. Also, given a constant cold tip temperature, a cryocooler requires less power at lower thermal loads. By implementing one cryocooler on the outside of the insulation system, where the thermal load is high, but at a warmer temperature, and implementing one cryocooler right at the coil working at a low temperature and low thermal load, an optimum operating power can be achieved. Here a system of two cryocoolers was analyzed. Figure 3 shows that when the outer cryocooler is operating at 78 Watts and extracting 21 thermal watts, the optimum total cryocooler power is approximately 200 Watts. This is for a large EMFF system with a one meter radius coil using a single vacuum gap for insulation. The thermal environment analyzed the worst case heating from the sun for a single coil in steady-state. Given a smaller sized coil using the insulation system in Fig. 2, the heat extraction required by the cryocooler(s) is significantly reduced and the power needed could be lower than 50 Watts.

The current plan of approach is to utilize three types of models to reach confidence on developing a flight-like thermal system. The nature of these models is analytic, discrete, and analog or experimental and is summarized in Table 1. For experimental validation it is sufficient to analyze a single HTS coil. The coil shown in Fig. 2 will be enclosed in a vacuum chamber with cooling provided by liquid nitrogen since a liquid nitrogen feedthrough is simpler and more cost effective than a cryocooler. Uniform heating due to radiation from the wall provides the heating environment for the coil. The coil is in contact with a thermal conductor and wrapped in MLI. The current model uses a copper tube as the thermally conductive jacket. A more complex design can be analyzed once this simpler system is modeled in simulation and its performance, i.e. the time-vary temperature distribution, is verified experimentally. The models described in the following section details the chamber model.

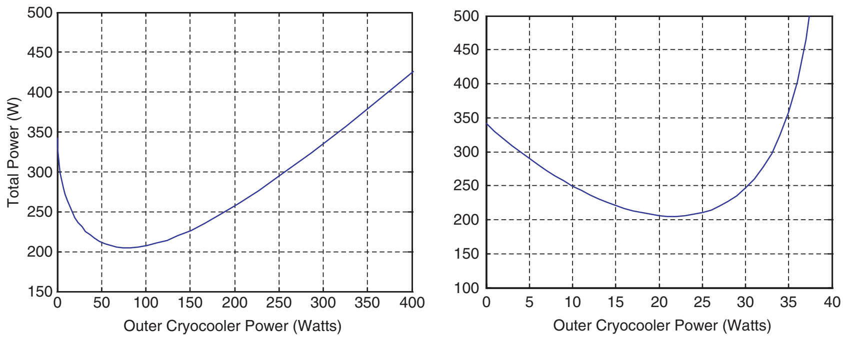



**Fig. 3** Total power requirements using two cryocoolers

**Table 1** Plan for current approach

| | Analytic | Discrete | Analog |
|---|---|---|---|
| Purpose | Mathematical model of temperature distribution based on first principles | Finite difference model simulates temperature distribution | Experimental verification of analytic and discrete models |
| Benefits | High fidelity and strong understanding | Ability to add non-uniform parameters and well used codes | Final verification of model, increases TRL of EMFF |
| Limitations | Nonlinear Radiation term makes solution complex | Large models are computationally expensive | Implementing model & environment accurately is challenging |

## 2.1 Analytic Model

A 3-D analytic model in cylindrical coordinates $(r, \theta, z)$ has been developed for the temperature distribution for the coil system shown in Fig. 2. Both the thermally conductive jacket and the MLI are modeled forming a two-layer model for a coil with length, $l$. The function for the temperature distribution has the following form consisting for Bessel functions $(I_n, K_n)$ and sinusoids:

$$\begin{aligned} T(r,\theta,z) = & \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\left(A_{mn} I_n\left(\tfrac{m\pi}{l}r\right) + B_{mn} K_n\left(\tfrac{m\pi}{l}r\right)\right)\cos n\theta \cos(\tfrac{m\pi}{l}z) \\ & + \sum_{m=1}^{\infty}\left(C_m I_n\left(\tfrac{m\pi}{l}r\right) + D_m K_n\left(\tfrac{m\pi}{l}r\right)\right)\cos(\tfrac{m\pi}{l}z) \\ & + \sum_{n=1}^{\infty}\left(E_n r^n + F_n r^{-n}\right)\cos n\theta + G\log r + H \end{aligned} \tag{1}$$

where the constants ($A$ through $H$) are solved for by applying orthogonality and the boundary conditions. The boundary condition given at the outer MLI layer is a linearized form of the radiation from the chamber wall and from the coil itself radiating outwards. At the inner copper layer, the cryocooler was modeled to extract heat from a small segment of the coil. The analytic model determined that MLI is a promising insulation material. It also showed that a simple conductor may not be sufficient as the thermal jacket around the HTS, because it exhibits a large temperature spread away from the cryocooler. Placing multiple cryocoolers along the coil is a possible solution, but comes with mass and power penalties. The limitations of the analytic model were that it contained a linearized radiation approximation and did not model the anisotropic properties of the MLI. For these properties, the finite difference model was used.

## 2.2 Finite Difference Model (FDM)

The discrete model of the thermal system finite differences the coil in three dimensions. A time-varying implicit model has been constructed for the thermally conductive jacket. This is an improvement over the analytic model, which was a steady-state model. This time-varying FDM can be used to examine the transient cooling response of the coil. The anisotropic property of the MLI has also been modeled. There is a thermal conductivity perpendicular to the radiation shields, $K_r$, which acts through the MLI layers, and a thermal conductivity parallel to the radiation shields, $K_\theta$, acting along a MLI layer. The heat diffusion equation is used as a starting point and is finite differenced so that the temperature at each node can be solved by Gaussian Elimination.

Figure 4 illustrates the general procedure used by the FDM for a one dimensional model. The FDM can use either a fixed temperature boundary condition or flux boundary condition at the cold point where the cryocooler is located. A control

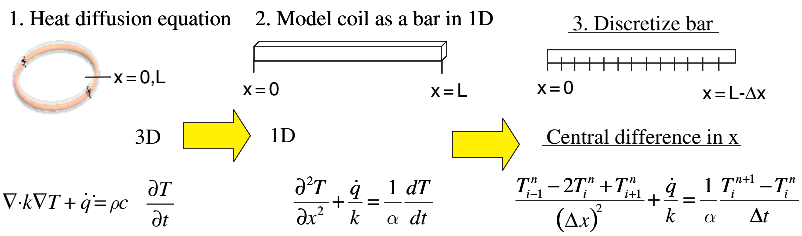



**Fig. 4** Methodology for finite difference model for a 1-D system

volume approach is used at the boundary conditions to determine the temperature at the outside and inside surfaces. Similar to the analytic model the FDM consists of the inner copper jacket layer and the outer MLI layer, which is the EMFF thermal design from Fig. 2. The outer boundary accounts for the radiation from the chamber walls (or deep space) and from the coil body, which is a function of temperature to the fourth power. The volumetric heat input into each node for a simplified 1-D model is expressed by:

$$\dot{q} = \begin{cases} \dfrac{q_{cryo}}{\text{Volume Element}}, & x = 0 \\ \dfrac{\varepsilon_t \sigma \left[T_w^4 - \left(T_i^n\right)^4\right] A_c}{\text{Volume Element}}, & x > 0 \end{cases} \tag{2}$$

where $q_{cryo}$ is the heat extracted by the cryocooler (or liquid nitrogen) located at the origin, and $T_i^n$ is the temperature of the coil at a location $i$ at time $n$. The effective emissivity, $\varepsilon_t$, accounts for the emissivity of both the chamber walls and the test article and their view factor. In addition, the model captures the effect of free-molecular flow in the chamber and also the variation of thermal diffusivity, $\alpha\left(T_i^n\right)$, as a function of temperature. The heat flux into the coil due to free-molecular flow is given by:

$$q\left[{}^{w}\!/_{m^2}\right] = F_a G p \left(T_2 - T_1\right) = h_{eff}\left(T_{CU} - T_w\right) \tag{3}$$

where the effective convection coefficient, $h_{eff}$, is largely a function of p, the system pressure. It was found that the free-molecular flow is a very low order effect on the system.

For comparison with the Matlab models, a simple 1-D model of the copper tube consisting of 19 nodes was constructed in a commercially available thermal code called Sinda. The Sinda model represented the experimental setup used in the chamber.

## 2.3 Experimental Model

A toroidal vacuum chamber was designed and built by MIT and Payload Systems Inc. as a testing facility for the thermal design and is shown in Fig. 5. The chamber, constructed out of COTS Polyvinyl Chloride (PVC) tubes, has a major radius of

1 m, minor radius of 12.5 cm, and holds a high vacuum ($10^{-5}$ Torr). Currently a copper tube is used as the test article to represent the thermally conductive jacket. A liquid nitrogen feedthrough enters the chamber and wraps around the copper article so that conduction with the liquid nitrogen tubing provides cooling for the entire article and acts as the cryocooler. Three plastic spacers support the copper tube. Ten thermocouples are inside the chamber via two instrumentation feedthroughs. It has been shown that the experiment is repeatable. A single tank of liquid nitrogen allows for approximately 3 hours of cooling time. The transient cooling data of the copper tube was used for comparison with the simulation models.

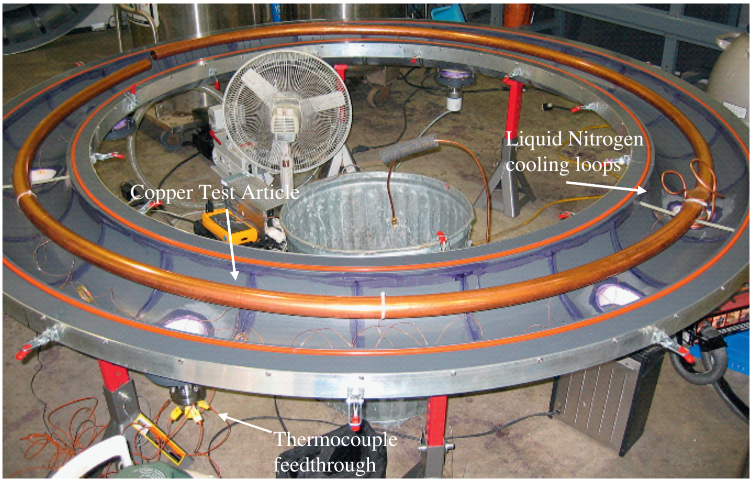
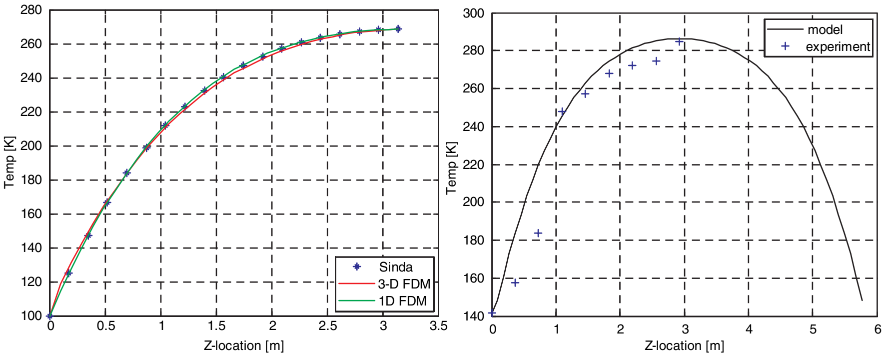



**Fig. 5** Experimental vacuum chamber (opened) for EMFF thermal system

## *2.4 Model Comparison*

Simulation models that were created include a 1-D FDM, 3-D FDM, and Sinda model. It has been shown in Fig. 6a that all three of these models match each other for a one meter coil (modeled as the copper test article) in the experimental vacuum chamber. The boundary condition used at the cryogenic cold finger was a fixed temperature of 100 K. The temperature increases as distance along the coil circumferentially (z-direction) increases and the maximum temperature is located opposite the coil, as expected.

To match the experimental model, the 3-D FDM was expanded to use the experimental data for the wall temperature and cold point temperature at the liquid nitrogen feedthrough. Overall, the experimental data had a faster transient cooling rate than predicted by models, however the FDM matched the experimental data to within 10 K at the end of the data run (approximately 3 hours), which is shown in Fig. 6b. The figure shows the temperature along the coil according to the model (solid line) and at nine thermocouple locations. Discrepancies between the model




a) b)

**Fig. 6** **(a)** Comparison of finite difference models (1-D, 3-D) and Sinda, **(b)** Comparison of experimental results with FDM

and the data are due to the film layer formed in the liquid nitrogen cooling loops which give unsteady cooling. Also heat introduction from the spacers holding up the test article and through the thermocouple wires are not incorporated in the model. While the maximum temperature of the design with just the thermally conductive jacket is higher than $Tc$, the Matlab models can now be run with the MLI incorporated in the design. Current results indicate that even with MLI the maximum temperature is greater than $Tc$. In order to obtain a more uniform temperature distribution around the coil, a heat pipe operating at cryogenic temperatures can be used. The heat pipe acts as the thermal conductive jacket and the HTS wire stack is located inside the pipe in the vapor space. Preliminary design of the heat pipe using multiple screen mesh layers as the wicking structure and using nitrogen as the working gas allows for a heat pipe with sufficient power capacity, in the tens of Watts, to cool the entire coil. Implementation of the cryogenic heat pipe is currently underway.

## 3 Conclusions

Electromagnetic formation flight is a unique and promising method of actuation for formation flight systems. The thermal system is a critical aspect of the design for an EMFF system since constant low temperature control of the superconducting coils is required despite a large variation of heating environments possible in low Earth orbit. The current thermal system design consisting of multilayer insulation and a thermally conductive jacket to maintain uniform temperatures around the coil has been modeled analytically and using finite difference models. These models correlate well in an experimental chamber set up for testing the thermal design. Additional work done on modeling include accounting for possible heat losses due to structural connections in a flight design and including the time-vary effects of the heating environment while in orbit. Future tests with MLI and the integration of the heat pipe with the HTS wire stack need to be conducted. For final validation, it is proposed to use a thermal vacuum chamber, to incorporate a sun and earth heat source and include the radiator in the EMFF thermal system.

## References

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