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# Cryogenic Heat Pipe for Cooling High-Temperature Superconducting Coils

Daniel W. Kwon* and Raymond J. Sedwick†
*University of Maryland, College Park, Maryland 20742*

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**An emerging method of propellantless formation flight is the use of electromagnets coupled with reaction wheels called electromagnetic formation flight. To create a large magnetic field necessary for actuating formation-flying spacecraft, electromagnetic formation flight uses high-temperature superconducting wire. To achieve superconductivity, the high-temperature superconducting wire requires a consumable-free cryogenic thermal control system to maintain the wire temperature below the critical temperature throughout the entire electromagnetic formation-flight coil, which could be as large as 2 m in diameter. The research in this paper investigates a consumable-free method of maintaining isothermalization for a large-scale high-temperature superconducting coil. The high-temperature superconducting coil resides inside a thermally conductive jacket that is used for isothermalization. Both a solid conductor and a heat pipe were investigated for use as the thermally conductive jacket. In this paper, a proof-of-concept circular cryogenic heat pipe was tested in a 2-m-diam toroidal vacuum chamber. This system showed the potential for high-temperature superconducting cooling. The experiments in this paper demonstrate the feasibility of operating large high-temperature superconducting coils for future formation-flying missions.**

## I. Introduction

AN INCREASING number of missions are considering multiple spacecraft flying in close proximity to replace traditional large monolithic space systems. Examples include formation-flying space interferometers such as NASA's Terrestrial Planet Finder Interferometer [1], ESA's Darwin mission [2], and fractionated spacecraft designs developed by Brown and Eremenko [3]. One of the challenges for formation-flying systems is that the amount of propellant available puts a constraint on mission lifetime and $\Delta V$ capabilities. An emerging method of propellantless formation-flight propulsion is the use of electromagnets coupled with reaction wheels. This technique is called electromagnetic formation flight (EMFF). The system is powered by the sun through solar arrays and does not rely on propellant for formation-flying maneuvers. Reducing a satellite's dependence on propellant can change current design methods for future spacecraft formations. For example, the amount of propellant required is currently determined using the rocket equation, and the $\Delta V$ required for formation flying is typically a parameter used in the calculation. For propellant-based systems, one method of minimizing propellant mass is to reduce the formation-flying $\Delta V$. Because EMFF is propellantless, the rocket equation is not used. Therefore, by using EMFF, the formation-flight propulsion system can be based on the desired formation performance, without any fuel constraints [4]. As a result, EMFF opens up new capabilities for satellite formations that might have had $\Delta V$ requirements that were too costly in terms of propellant to even consider before. Another advantage of EMFF over traditional propellant-based thrusters is the elimination of impinging thruster plumes, which can cause ablation of nearby spacecraft surfaces and produce unwanted vibration excitation. Applications of EMFF are not just restricted to station-keeping fractionated spacecraft architectures or maintaining sparse aperture systems. The electromagnetic (EM) coils can be used with multirole functionality, such as power transmission, torque for slew control, or for passive offensive or defensive capabilities in military satellites [5,6].

To implement EMFF, an EM dipole is created by running current through an electromagnetic coil. A conceptual drawing of an EMFF vehicle is shown in Fig. 1. The EM dipole creates coupled forces and torques on nearby satellites that also have at least one EMFF coil. A satellite with three orthogonal coils can create a steerable dipole in three dimensions. Similarly, a set of three orthogonal reaction wheels is necessary to decouple the forces and torques in three dimensions. Consequently, the EM coils in concert with reaction wheels allow for all the necessary actuation in relative degrees of freedom for a formation-flight array [7]. To create a large magnetic moment to generate large forces, coils that can carry a large current and are large in size are favorable for EMFF.

The high-temperature superconducting (HTS) wire is an enabling technology for EMFF because it allows the creation of a large dipole moment. One of the challenges of using HTS is maintaining the cold temperature necessary for operation. The entire length of the superconducting wire must be maintained below a critical temperature for it to operate at superconducting levels. Commercial off-the-shelf (COTS) wire from American Superconductor Corporation has a critical temperature $T_{\text{critical}}$ of 110 K ‡. For EMFF satellites in the proximity of Earth, such as low Earth orbit (LEO) or geosynchronous Earth orbit, heat flux from the sun and Earth needs to be rejected To maintain temperatures below $T_{\text{critical}}$. This heat flux has the potential to rapidly change in both magnitude and direction, depending on the satellites' orientation. Heat into the coils can be rejected using cryocoolers and various types of insulation such as multilayer insulation (MLI). One characteristic of the HTS wire is that more current can be driven through the wires at colder temperatures, 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. In addition to this coupled behavior, the thermal system must also be consumable-free, because EMFF obviates the need for consumables for formation-flying maneuvers. The EMFF thermal system is a unique problem in the topic of cooling large space structures without the use of consumables.

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*Faculty Research Assistant, Department of Aerospace Engineering, 3181 Martin Hall. Member AIAA.

†Assistant Professor, Department of Aerospace Engineering, 3181 Martin Hall. Member AIAA.

‡Data available online at http://www.amsuper.com/ [retrieved 2 February 2007].