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A DUAL FUNCTION MAGNETOHYDRODYNAMIC (MHD) DEVICE FOR ANGULAR MOTION MEASUREMENT AND CONTROL

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The principles of magnetohydrodynamics (MHD) have been exploited by Applied Technology Associates for the design, development, and commercial production of a family of inertial angular motion sensors. This paper discusses an innovation in MHD technology that results in a device that both measures angular motion and generates torque. The MHD actuator/sensor is ideal for space applications requiring precision attitude control or stabilized line-of-sight (LOS) control.

MHD sensors operate over wide bandwidths (1-1000 Hz) and exhibit performance at the state-of-the-art. For instance, sensors have been delivered for use in spacecraft motion measurement functions with noise floors that fall below 0.008 arcsec rms. The MHD torque generator is capable of providing spacecraft attitude control consistent with such levels of residual motion. In a single MHD device low levels of angular motion can be measured and control torques created to stabilize a spacecraft or its instrument payload.

A representative MHD pitch control actuator for a small spacecraft application (580 kg class satellite) exhibits peak torque capability of 1.2 Nm, operates over a bandwidth up to 1000 Hz, and occupies a physical volume of 21 cm (D) by 6 cm (H). The mass of the MHD actuator and sensor is 3.77 kg. As has been demonstrated with MHD sensors, practical designs can be configured in sizes that span multiple orders of magnitude. A MHD sensor such that two would fit within the volume of a dime was commercially produced for a disk drive shock protection function.

The MHD actuator/sensor is especially suitable for the current and future generation of small space experiments needing precise, low-noise measurement and control of rotational motions. The MHD technology offers flexible design, reliable operation, and key performance advantages over more conventional approaches to angular motion measurement and control. In addition to applications in attitude control and payload LOS stabilization and pointing, other natural uses for the MHD actuator/sensor include rotary damping of deployable structures and devices and vibration insertion and cancellation.

INTRODUCTION

This paper describes a new technology for creating rotational torques in a package that is also capable of measuring the angular motion. This dual function actuator / sensor device uses the principles of magnetohydrodynamics (MHD). The notion of a combined device for rotation motion control and measurement is novel. The idea of an angular rate sensor based on the MHD principle has been in the commercial marketplace for more than a decade (Ref. 1). However, the proposed use of this principle to add the functionality of a control actuator to the MHD sensor and the verification of a design concept for a practical device is original with this paper.

The body of the paper includes two sections. In the first of these sections, we briefly review the physical principles that govern the operation of the MHD inertial rate sensor. The development history and commercial status of this technology are also noted. This serves as the prerequisite theory onto which we then add the theory of the MHD rotational actuator. The MHD angular rate sensor is fundamentally an electrical generator where the motion of the case (body on which it is attached) induces current flow. To devise an MHD rotational actuator, the generator is converted into a motor. That is we connect an electrical source and create motion. After these sensor and actuator basics are described, the next section then proceeds to put forward a design concept for a practical device suitable for use in spacecraft pointing. The top-level requirements for a spacecraft pointing mission are identified and a design process described that leads to a dual function MHD device for measuring and controlling the spacecraft pitch. Simulation models are used to verify the functional and performance characteristics of the MHD actuator / sensor. The context in which the design is created and verified stems from a real spacecraft flight experiment known as the Relay Mirror Experiment (RME) that was launched in February, 1990 and operated successfully until March, 1991 (Ref. 2).

Sections that summarize the results and list key conclusions are given at the end of the paper.

MHD PRINCIPLES FOR SENSORS AND ACTUATORS

MHD Angular Rate Sensor Background

The initial MHD inertial angular rate sensor arose from an R&D project conducted by Applied Technology Associates in the early 1980’s under sponsorship of the United States Air Force. The thrust of the project was to identify, design and fabricate sensors capable of measuring low-level, wide-bandwidth inertial angular vibrations in environments associated with opto-mechanical systems for pointing laser beams. The vibration environments to be measured by the new sensor exhibited amplitudes at microradian levels over the frequency band of 1-1000 Hz. After a search of the available technologies, ATA determined that it was feasible to use the MHD principle as the basis for precision angular vibration sensors.

Figure 1 illustrates the principle of operation of the MHD inertial rate sensor.

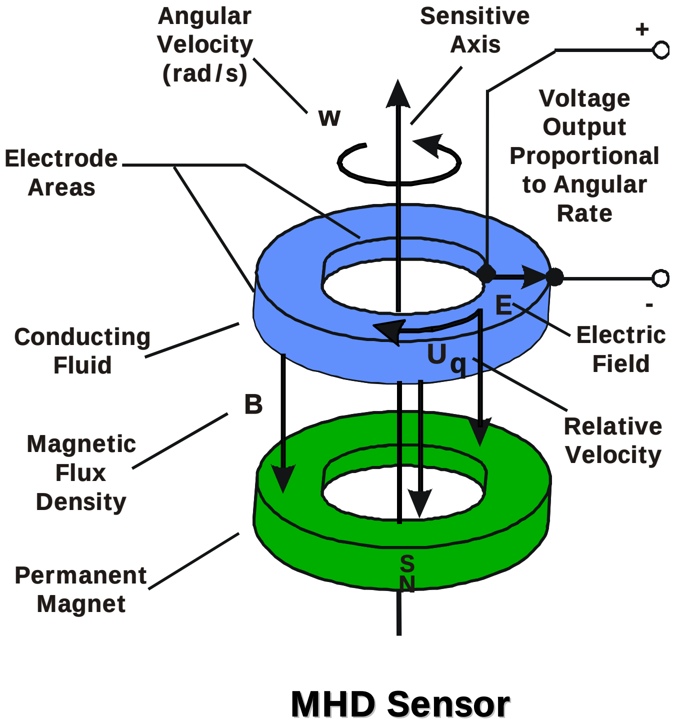

Figure 1 Illustration of the MHD Sensor Operating Principle

The lower ring is a high-performance permanent magnet that creates a magnetic field normal to its surface. Magnetic flux lines of this field are denoted with the symbol B. The upper ring is an annulus of conductive fluid. The magnet is fixed to a cylindrical case and the whole attached to a body for which inertial angular motions are to be measured. If the body and the attached sensor rotates with an angular velocity w, a relative velocity U_q will occur between the magnetic field B and the conducting fluid. The moving flux cutting the stationary conductive fluid imparts an electric field E normal to the plane defined by the relative velocity vector U_q and the magnetic flux B. This electric field is radial everywhere to the conducting fluid annulus. With the top and bottom of the fluid annulus insulated and the inner and outer perimeters of the fluid annulus in contact with electrodes, the voltage between the electrodes may be measured. This voltage will be dependent on the relative fluid velocity. In situations when the sensor case and body to which it is attached are moved with high frequency vibrations, the fluid will remain inertially fixed and the voltage across the electrodes will be linearly related to the inertial angular rate of the sensor case and body.

The sensor transfer function between rate and output signal is defined by Eq. (1) below.

$$H(s) = K_{amp} Brw\, S \Big/ (S + v(1 + M^2)/h^2) \tag{1}$$

In the equation, the symbols denote the following:

S = Laplace operator
B = applied magnetic flux density (T)
r = rms radius (m)
h = channel height (m)
w = ro-ri, effective channel width (m)
η = resistivity of mercury, 9.58e-7 $(\Omega\, m)$
ν = kinematic viscosity, 1.15e-7 (m^2/s)
ρ = density of mercury, 1.354e4 (kg/m^3)
M = $Bh \Big/ \sqrt{\rho \nu \eta}$ = Hartmann Number (unitless)

Subsequently the basic MHD rate sensor principle illustrated in Figure 1 led to development, manufacture, and commercial offering of a diverse family of rate sensor products to serve in various applications. Figure 2 is a photograph of one of the recently released models known as the Model ARS-12.

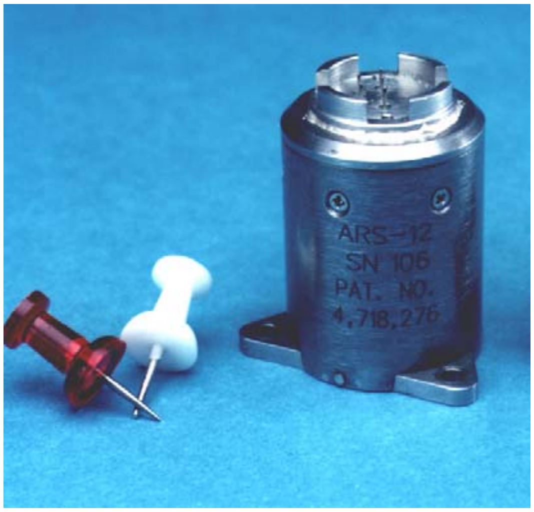

Figure 2 Photograph of High Performance MHD Angular Rate Sensor

The sensor exhibits a measurement bandwidth that exceeds 1000 Hz, measurement noise below 0.021 arcsec (100 nrad) noise equivalent angle (NEA) over the frequency interval 1-1000 Hz, 100 dB dynamic range, and low g-sensitivity and axis cross-coupling. The size of the sensor pictured is 2.54 cm (D) by 3.3 cm (H); mass less than 100 grams, and power draw less than 0.3 W.

The version of the sensor in Figure 2 has been packaged and qualified for use in spacecraft applications such as the next generation of Geostationary Operational Environmental Satellites (GOES), and the Advanced Land Observing Satellite (ALOS), and the next generation of Global Positioning Satellites (GPS). Other MHD sensor models have been designed and produced to address applications such as safety testing in the automotive industry, shock protection for disk drive writing mechanisms, missile and artillery projectile instrumentation and flight controls. The flexibility and versatility of the MHD principle used in precision angular rate sensors bodes well for it application also in creating a family of MHD actuators and dual-function packages. The next subsection addresses this area.

MHD Actuator

After working with the principles and applications of MHD angular rate sensors for almost two decades, it was a natural leap to conceptualize the MHD angular actuator. From the generator realization of the MHD sensor the realization of the MHD actuator follows in due course. Figure 3 illustrates the actuator principle of operation.

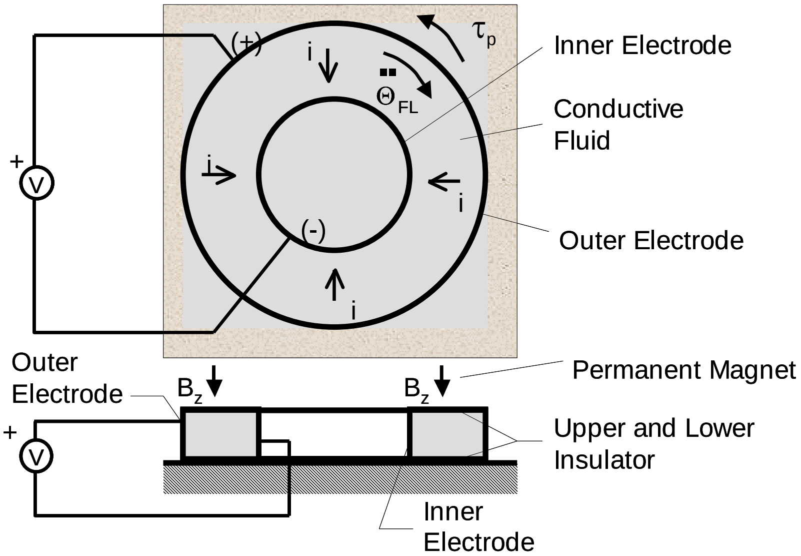

Figure 3 MHD Actuator Principle of Operation

Just as in the configuration of the MHD sensor, the configuration of the MHD actuator involves a permanent magnet ring and an annulus of conductive fluid. The case holding the two annular components is attached to a body. In this instance, we want the actuator to apply torque to the body. The fluid annulus has electrodes on the inner and outer perimeter. Electrically insulating materials form the top and bottom of the fluid annulus. Now instead of measuring the voltage between the two electrodes, we connect a power source to the electrodes and cause current to flow along radial paths between them. The flowing current i interacts with the magnetic field Bz causing the fluid to accelerate and rotate within the fluid annulus. The angular momentum increase of the fluid induces a torque on the actuator case (and the body on which it is mounted).

The equations that represent the device displayed in Figure 3 are given below:

$$\ddot{\theta}_{FL} = \frac{\upsilon}{h^2}\left(\dot{\theta}_{CASE} - \dot{\theta}_{FL}\right) + \frac{BI}{A\rho r} \qquad (2)$$

$$\tau = J_{FL}\ddot{\theta}_{FL} \qquad (3)$$

Where

υ = kinematic viscosity (m^2/s)
h, r = channel thickness (m), channel rms radius, (m)
B = channel flux density (T)
A = channel mean cross-sectional area (m^2)
ρ = fluid density (kg/m^3)
$\ddot{\theta}_{FL}$ = fluid angular accelaration (rad/s^2)
$\dot{\theta}_{CASE}$ = actuator case velocity (rad/s)
J_{FL} = fluid mass moment of inertia ($kg\text{-}m^2$)
τ = transmitted torque
I = current (A)

The principles of operation and governing equations have been established. Now it remains for us to start from a set of typical actuator requirements and verify that it is feasible to arrive at a practical design (size, mass, power, performance, etc). The next Section is devoted to this topic. We are going to focus on the MHD actuator first, establish its design, and then confirm that the resulting actuator will work also in the sensor mode of operation.

CONCEPT DESIGN FOR DUAL-FUNCTION MHD ACTUATOR / SENSOR

MHD Actuator Requirements

In the years from 1986 through 1991, a Relay Mirror Experiment (RME) was undertaken to demonstrate that a low-power laser could be transmitted from one ground site, reflected from a mirror on an orbiting satellite, and precisely pointed to hit an array of scoring sensors at a second ground site. During demonstrations of the laser relay function, it was necessary to orient the spacecraft to accurately point at a fixed ground location on a line between the laser source site and the target site. We have selected this spacecraft and the context of its pointing requirements to illustrate the feasibility of the MHD actuator /sensor. **Figure 4** depicts key ideas that comprised the RME.

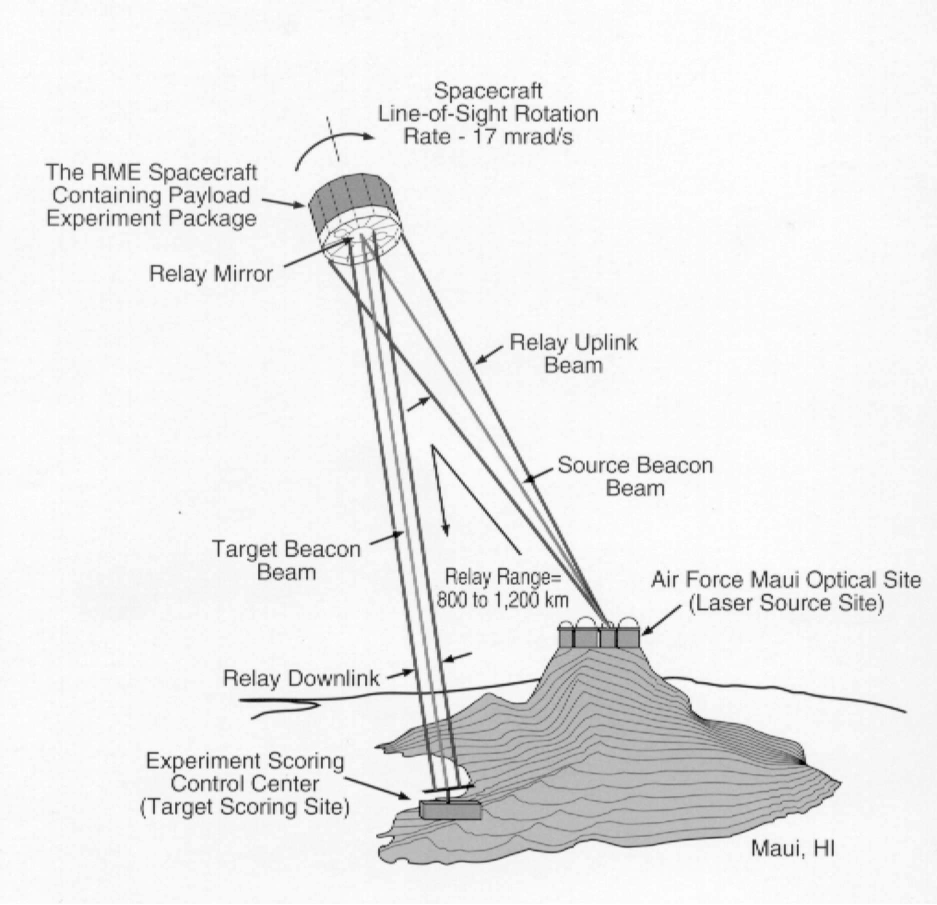

Figure 4 Two Ground Sites and an Orbiting Spacecraft Comprise the RME

There are a least a couple of motivations that make this spacecraft experiment interesting to use as a test problem. The spacecraft size is tractable and requirements data on which to base the MHD actuator design are readily available. In the original RME implementation, the attitude pointing function used a torque rod triad and a single reaction wheel. Our design concept verification approach is to show that the MHD actuator may be substituted for the RME reaction wheel and that the resulting spacecraft pointing functions and performance are satisfied. The Wideband Angular Vibration Experiment (WAVE) was also flown as part of the RME (Ref. 3). The WAVE was the first space flight validation of the MHD sensor technology. A sensor package containing MHD sensors to measure the spacecraft vibrations was developed an installed with the RME payload.

The illustrations in **Figure 5** allow us to identify and put down key requirements that must be considered in the design an MHD actuator to control the RME spacecraft motion during a typical test engagement.

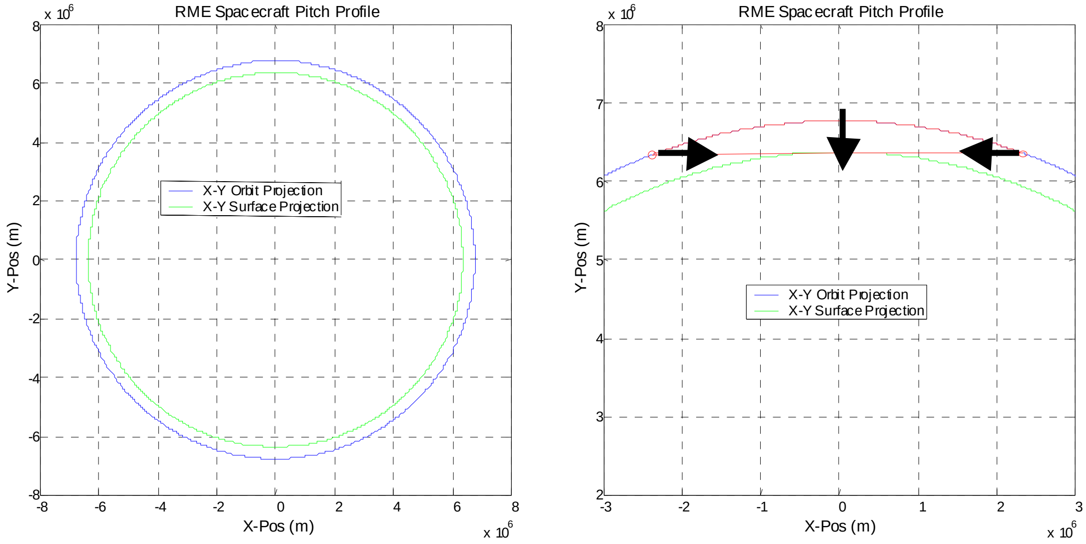

Figure 5 Geometry of the RME Spacecraft Orbit and Segment with Ground Site Engagement

The RME spacecraft operates in a 400-km circular orbit as shown in the left part of Figure 5. During the test engagement, illustrated in Figure 4, the experiment needs to have the spacecraft attitude controlled so that it remains accurately pointed to a fixed ground point. At the start of the engagement the spacecraft will appear on the horizon and will be pointed at the ground site. As it travels overhead the attitude will be controlled to keep it pointed to the ground site. At the end of the engagement the spacecraft will disappear over the horizon and its attitude will have experienced a pitch angle change of 180 degrees from start to end. **Figure 6** illustrates this needed pitch attitude behavior. The spacecraft operates in nadir pointing mode until the ground site appears on the horizon. Then it pitches up point to the site and follows a pitch profile that keeps the axis of the spacecraft pointed to the ground site.

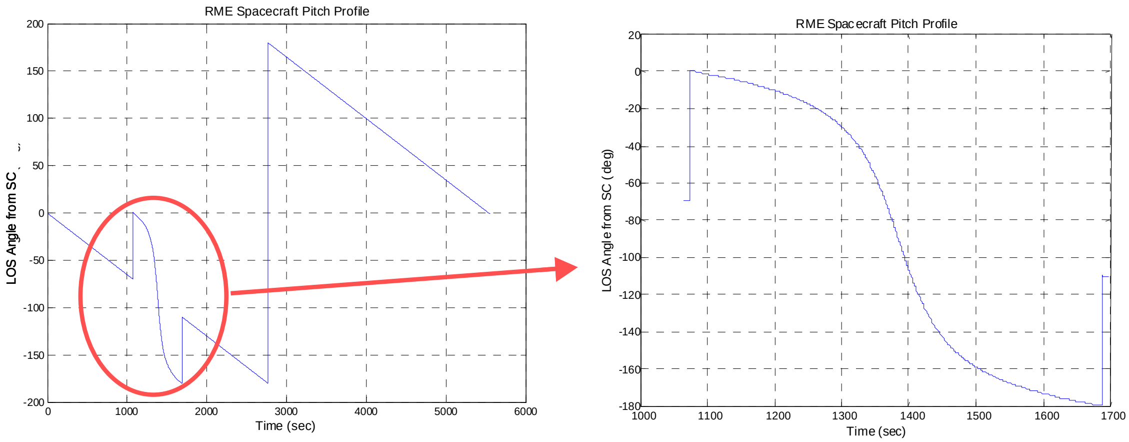

Figure 6 Pitch Attitude of RME Spacecraft During Orbit Cruise and Test Engagement Segment

The angular rate and angular acceleration of the spacecraft during the test engagement are illustrated in **Figure 7**.

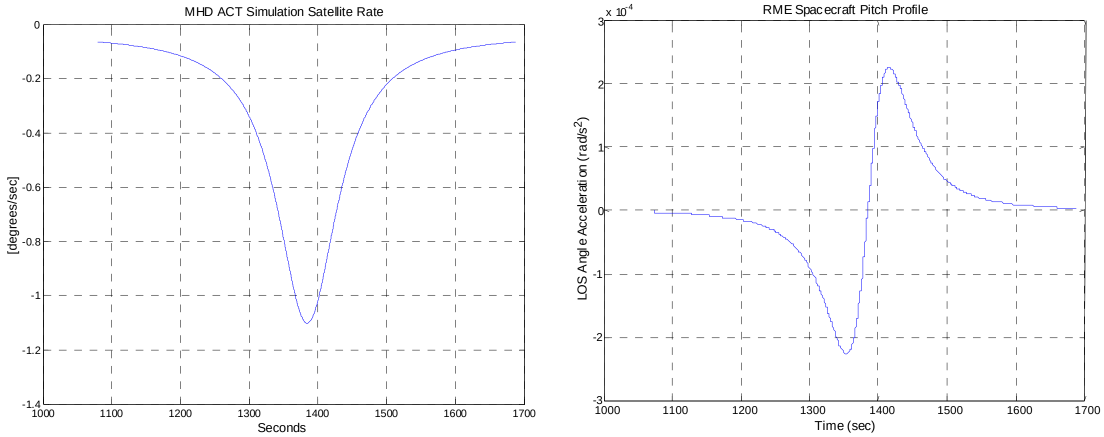

Figure 7 Angular Rate and Angular Acceleration of RME Spacecraft

The graphs of Figure 7 allow us to set the key design requirements for the MHD actuator. The maximum angular velocity of the spacecraft (0.02 rad/s) and its pitch moment of inertia (250 kg-m^2) define the maximum angular moment change of the spacecraft. Thus, the MHD actuator needs the capability to provide angular momentum change greater than 4.7 Nm-s. If we set a maximum rotational velocity for the fluid in the actuator, an implied fluid moment of inertia results. It is assumed that the maximum rotation rate of the fluid should be less than 1050 rad/s (or 10,000 rpm). The maximum angular acceleration (2.26e-4 rad/s^2) and pitch moment of inertia (250 kg-m^2) sets the maximum required torque from the actuator (0.06 Nm).

MHD Actuator Concept Design

The top-level requirements above let us select the parameters for the MHD actuator. Using a fluid annulus that has an outer radius of 10 cm, an inner radius of 8 cm, and a depth of 0.1 cm, we calculate the fluid moment of inertia for a single actuator disk as 0.00126 kg-m^2. The maximum torque capability from this single disk is 0.273 Nm with reasonable assumptions on the magnet flux density and actuator current. Checking both torque and angular momentum requirements, we find that at least 3 disks are needed to meet the angular momentum criteria. The torque requirement is not a limiting constraint.

Upon completing the requirements checks noted above, we can then complete the design concept and configuration. The minimum of 3 actuator disks is rounded up to 4 to give an even number (magnetic field balance and symmetry). Another disk is added to serve as the sensor function within the package. Again for symmetry (and for redundancy) we put one sensor disk on each end of the assembly. With the fluid annulus, the permanent magnet, and insulation material each disk is approximately 1 cm thick. The annulus dimensions and a case to hold all of the elements together dictate a package with an outer diameter of 21 cm and height of 6 cm. **Figure 8** illustrates the envelope for the MHD Actuator / Sensor device. Additional detail on the layout of the individual actuator / sensor disks is illustrated in the cross-section of the upper quadrant of the assembly. This cross-section is depicted in **Figure 9**.

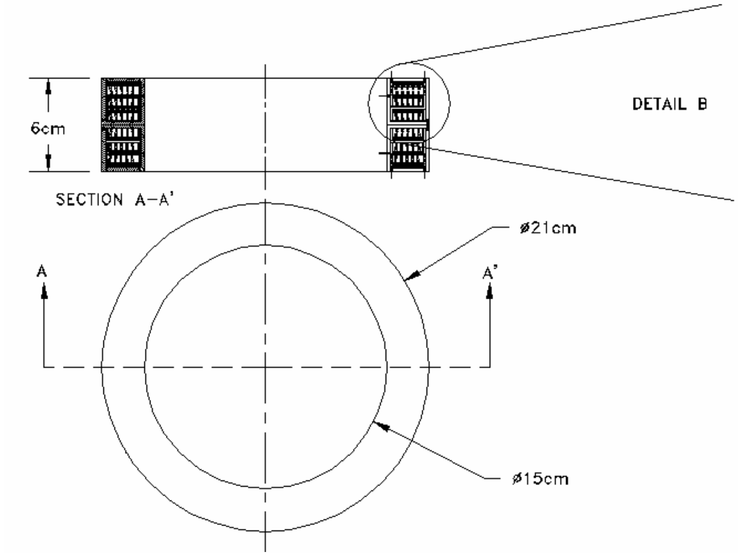

Figure 8 Envelope Drawing for the MHD Actuator / Sensor Assembly

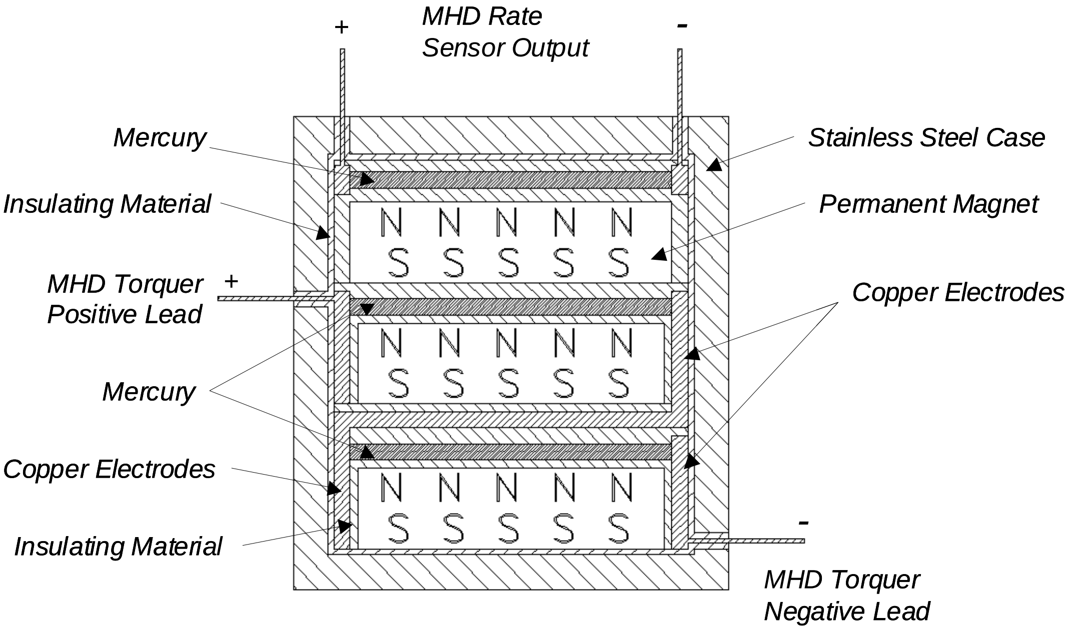

Figure 9 Cross-Section of MHD Actuator / Sensor Upper Right Quadrant

MHD Actuator / Sensor Design Verification

The concept design was verified by setting up a simple simulation of the RME spacecraft in orbit, executing the required pitch maneuver. Simulation models of the MHD actuator and sensor were implemented and a simple spacecraft rigid body model added. The operation of the system executing the desired engagement was simulated and the outputs from the model checked to verify that the requirements of attitude control were met. The simulated signals and characteristics of the MHD actuator /sensor were checked to see if they were consistent with the expected behavior and within practical regimes of operation.

Figure 10 depicts the time histories of the error in following the engagement rate profile and commanded attitude angle. The maximum rate error of 0.00012 deg/s and pointing error of 0.0025 deg are very acceptable.

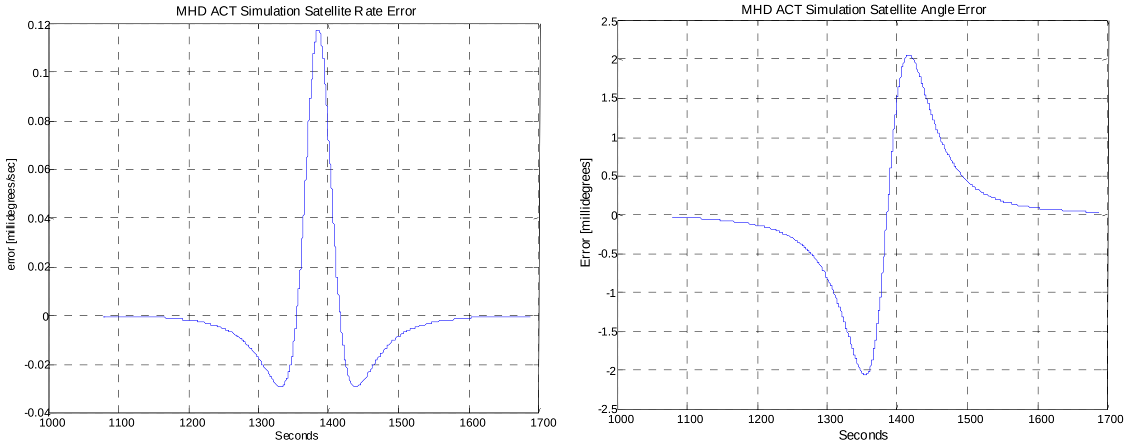

Figure 10 MHD Actuator / Sensor Performance Results in Small Rate and Angle Errors

We then examine the actuator torque and current during the interval of the engagement. The simulated torque from the actuator exactly overlays the required torque to produce the desired spacecraft acceleration profile. The current profile follows the angular rate profile of the engagement. This indicates that in the actuator dynamic behavior, the viscous drag of the fluid in the case is dominant. **Figure 11** provides plots of the simulation model results.

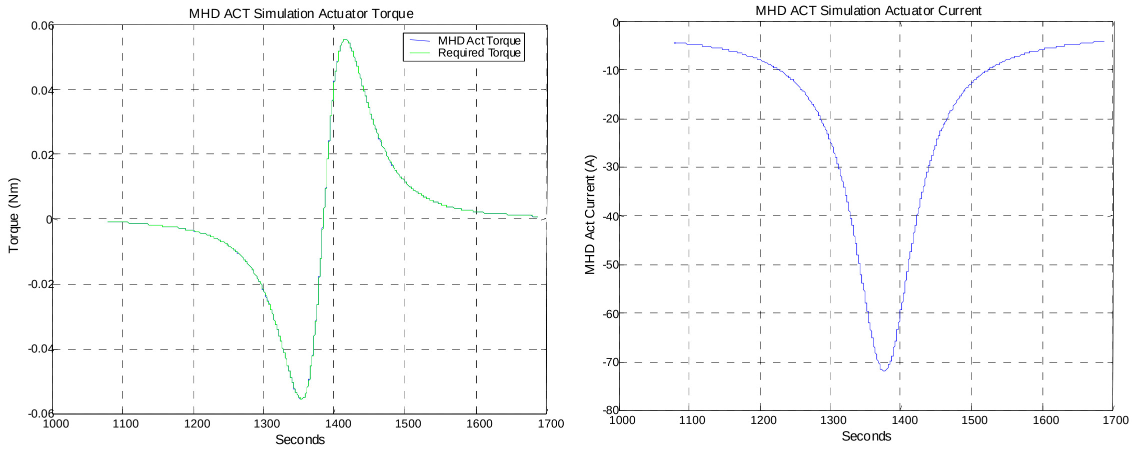

Figure 11 Simulated MHD Actuator Torque and Current

As the final step in the verification process, we examine the simulation variables corresponding to the fluid rotation rate and the output signal from the MHD sensor. The fluid rate signal follows the trend of the spacecraft attitude rate as expected (equal angular momentum). Furthermore the maximum rate is less than the 1050 rad/s (10,000 rpm) set as a design constraint. The output signal from the MHD angular motion sensors in the package reach 5 volts, levels sufficient for implementation of the rate feedback loop included in the attitude control system.

RESULTS SUMMARY

The principles and technology of MHD were employed to create a dual function rotational actuator and motion sensor. A concept design has been defined for an MHD actuator / sensor assembly to perform the attitude control functions that were required in the RME. The requirements of accurately pointing the spacecraft to a fixed ground location while in view of this site were met. In doing so, the actuator / sensor assembly operated in regimes of power and rotational velocity that are quite practical. The physical size of the concept design is reasonable at 6 cm high and 21 cm in diameter. The actuator provides for the angular momentum interchange and the self-contained angular motion sensor facilitates a rate feedback controller in the spacecraft pointing system. Maximum power required by the MHD actuator during the simulated engagement was 4.9 W.

CONCLUSIONS

The analyses and simulations performed in preparing this paper and our experience with designing and manufacturing MHD angular motion sensors lets us draw the conclusion that an MHD actuator is quite feasible. A number of inherent advantages of this technology beyond its dual functions of measurement and control are evident. The absence of moving mechanical parts supports high reliability, low manufacturing costs, and successful operation in space applications. The MHD principles and technology lend themselves to great flexibility. Devices may be designed for a wide range of applications with different torque and momentum needs. The combined sensor and actuator is especially consistent with meeting pointing control and stabilization requirements for small (micro) spacecraft with state-of-the-art optical instruments. The no rotating mechanical elements feature minimizes vibrations that would degrade optical instrument image collection performance. The MHD principle also produces torque that is free of ripple.

ACKNOWLEDGMENT

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REFERENCES

1. D. Laughlin and D. Smith, “ARS-12G inertial angular vibration sensor provides nanoradian measurement”, in *Acquisition, Tracking and Pointing XV*, Michael K. Masten, Larry A. Stockum, Editors, *Proceedings* of SPIE, Vol. 4365, pp. 168-175, April, 2001.
2. J. Dierks, S. Ross, A. Brodsky, P. Kervin, and R. Holm, “Relay Mirror Experiment overview: a GBL pointing and tracking demonstration”, in *Tracking and Pointing V*, Michael K. Masten, Larry A. Stockum, Editors, *Proceedings* of SPIE, Vol. 1482, pp. 146-158, April, 1991.
3. J. Anspach, P. Sydney, and G. Hendry, “Effects of base motion on space-based precision laser tracking in the Relay Mirror Experiment”, in *Tracking and Pointing V*, Michael K. Masten, Larry A. Stockum, Editors, *Proceedings* of SPIE, Vol. 1482, pp. 170-181, April, 1991.