

The Design of the OPAL Attitude Control System

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Abstract

OPAL's attitude is controlled by using two pairs of magnetic coils and a three axis magnetometer. One pair of coils is mounted on the side panel where the picosatellite launch window is located. The other pair is mounted on the bottom panel. The primary requirements of the attitude control system are to decrease spin of the satellite with respect to its body axis to minimize disturbances during picosatellite launch, and to spin up the satellite once the picosatellite is launched to meet thermal requirements. To meet these requirements the "minus Bdot" control law was used. This paper will describe the design and testing of the OPAL attitude control system.

Introduction

The Orbiting Picosatellite Automatic Launcher (OPAL) is the second Satellite QUICK Research Testbed (SQUIRT) satellite designed and built by students in the Space Systems Development Laboratory (SSDL) at Stanford University. It's primary mission is to test the feasibility of launching several picosatellites from the main satellite. Each picosatellite has attitude sensors, an experimental magnetometer, a microprocessor, a battery and a radio transmitter on board. Once launched, they will transmit data to the mother ship. More on information on the design of OPAL can be found on the SSDL home page: (<http://aa.stanford.edu/~ssdl/projects/squirt2/>).

In the original design, OPAL did not have an attitude control system. To allow minimal off-axis momentum to the picosatellites during the launch, its major moment of inertia axis is designed to be aligned with the picosatellite launch axis. This configuration eventually causes the satellite to spin along the minimum energy axis with small nutation. Since OPAL will be launched as a secondary payload on a yet to be determined launch vehicle, little is known about the dynamics of the launch or the final orbit. Due to the uncertain launch conditions, it was not possible to predict how long it would take to be

stable enough to deploy the picosatellites. It was this fact that led to the decision to implement attitude control on OPAL.

A number of different schemes were considered for OPAL's attitude control. These included pressurized gas thrusters, momentum wheels, a gravity gradient boom, and magnetic control. Upon investigation, it was determined that magnetic control offered several advantages over the other alternatives. The main advantages are that magnetic control is very simple to implement, requires no moving parts, is very light weight, and is highly compatible to the existing structural bus. High compatibility was extremely important since the bus design was already finalized, and making any significant changes would have added a great amount of complexity. An added advantage is that OPAL already has a three axis magnetometer that can be used in conjunction with the magnetic control. Once magnetic control had been chosen, magnetic coils were selected over magnetic torque rods due to the added complexity and cost of developing effective torque rods with very little hysteresis. The magnetic coils provide a sufficient magnetic dipole moment to be effective in damping out the motion of OPAL within an orbit period.

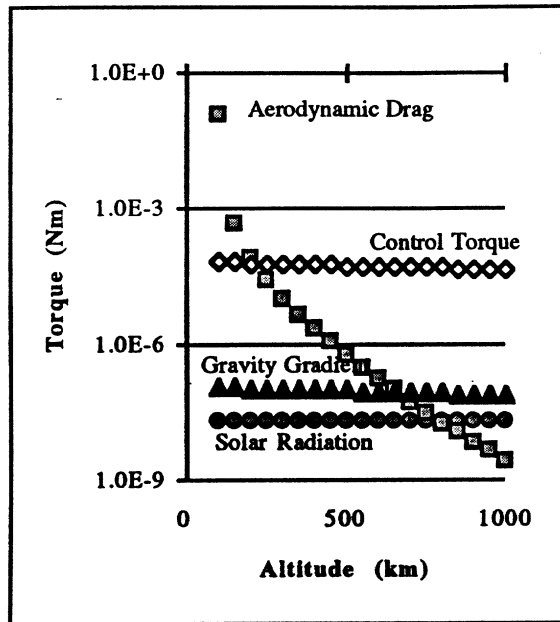
Attitude Control System Requirements

To be able to control the angular momentum of the satellite, the attitude control system must have enough control authority to overcome on-orbit disturbances such as external torque due to aerodynamic drag, solar radiation pressure and Earth's magnetic field. The aerodynamic drag is calculated using the MSIS atmospheric model and OPAL's

Table 1. Dimensions of OPAL

Height	23.5 cm
Outside Radius	21.0 cm
Mass	14.5 kg
Volume Envelope	27,300 cm ³
Usable Volume	21,300 cm ³
Moment Arm	5 cm

Figure 1. Disturbance Torques



physical dimensions, which are summarized in Table 1. Torque due to gravity gradient and solar radiation pressure are also calculated. The aerodynamic drag is the largest disturbance. Maximum possible values of disturbance torques, including gravity gradient torque, solar pressure torque, and aerodynamic drag, were compared with the average magnetic control torque and are shown in Figure 1. Notice that the magnetic control torque is

sufficient to overcome all disturbance torques past an altitude greater than 200 km.

Design

Coil design

At the altitude of 350 km, the largest disturbance torque is due to aerodynamic drag, which is on the order of $10E-6$ Nm. To control the satellite, a control torque on the order of $10E-5$ Nm is required. Since the available control torque is directly proportional to the dipole strength of the magnetic coil, a torque rod configuration was initially considered. However, due to the added complexity and cost of developing effective torque rods, such as selecting and acquiring core material, magnetic coils with no core were selected. Once the configuration was chosen, a series of tests were conducted to select the material and gauge of the coil, the number of turns, and the optimal operational voltage. Table 2 shows the summary of the coil selection study. The coils are run at 5V instead of 12V in order to reduce the bulk of the coil. Power consumption was used as a guide in selecting the number of turns once the voltage was set. Each coil was allocated one watt of power. No. 28 laminated copper wire was selected for the coil. The coils are located on the picosatellite launching side panel and on the bottom panel (figures 2 and 3). To maximize the dipole strength, brackets were made to hold the coils at the outer most perimeter of the each panel. Tables 3 and 4 show the characteristics of the coils.

Table 2. Coil Selection

Side Panel Coils (area: 0.0368 m ²)					
No. of turns	R (ohm)	V	I (A)	P (W)	Dipole Strength (Am ²)
1000	135	12	0.0892	1.0698	3.2764
500	67	12	0.1783	2.1397	3.2764
100	13	12	0.8915	10.6984	3.2764
500	67	5	0.0743	0.3715	1.3652
200	27	5	0.1857	0.9287	1.3652
100	13	5	0.3715	1.8574	1.3652

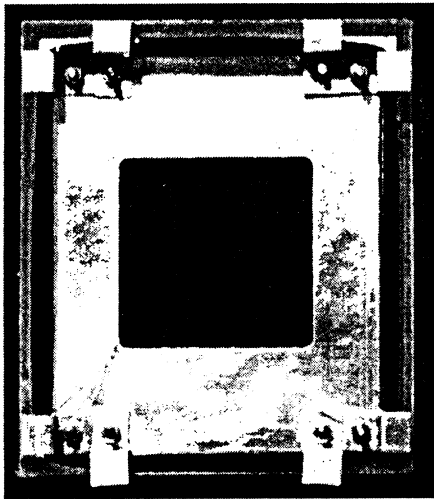
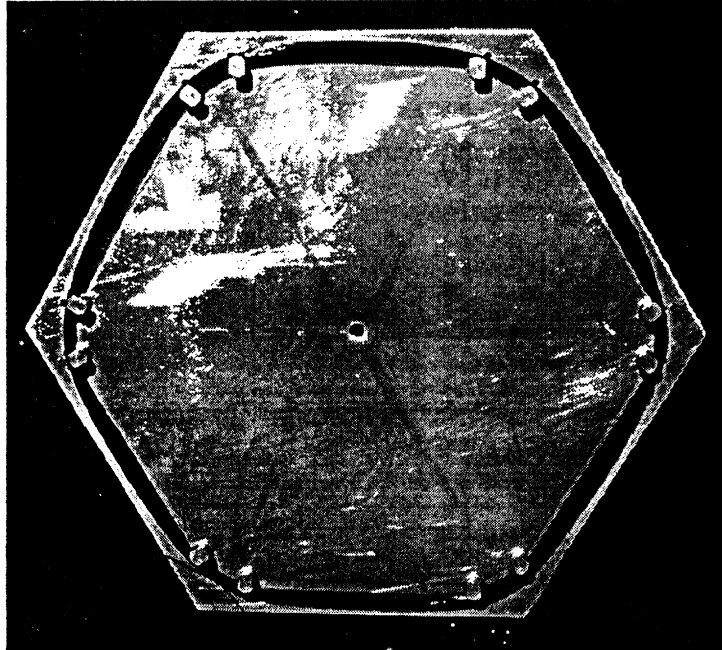
Bottom Coils (area: 0.0940 m ²)					
No. of turns	R (ohm)	V	I (A)	P (W)	Dipole Strength (Am ²)
1000	200	12	0.0600	0.7200	5.6400
500	100	12	0.1200	0.2500	5.6400
100	20	12	0.2400	1.4400	5.6400
500	100	5	0.0500	2.8800	2.3500
200	40	5	0.1250	0.6250	2.3500
125	25	5	0.2000	1.0000	2.3500

Table 3. Side Panel Coil

Coil Area	.0368 m ²
Coil Diameter	.07 m
Wire used	#28 Copper wire
Number of turns	200
Resistance	27 ohm
Running voltage	5 v
Current	186 mA
Power consumption	0.929 w
Dipole strength	1.37 Am ²

Table 4. Bottom Panel Coil

Coil Area	.094 m ²
Coil Diameter	.05 m
Wire used	#28 Copper wire
Number of turns	125
Resistance	25 ohm
Running voltage	5 v
Current	200 mA
Power consumption	1 w
Dipole strength	2.35 Am ²

**Figure 2. Coil on the Side Panel****Figure 3. Coil on the Bottom Panel**

CPU Interface

OPAL's computer consists of a primary CPU board and two peripheral data-acquisition boards. All boards are produced by Vesta Technology, Inc. The CPU is based the Motorola 68332 microcontroller. The peripheral boards contain two SPI332 boards based on Motorola's Serial Peripheral Interface bus and protocol.

The CPU gets information from the magnetometer through the following process. The outputs of the magnetometer are three bipolar voltage signals, each proportional to the magnetic field strength about a principal axis. These signals are fed directly into an analog to digital converter. The A/D interfaces to a serial port on the CPU through the SPI bus. The control software has access to these signals and decides which, if any, of the torque coils should be turned on. Each coil is controlled by two digital I/O lines, one for on/off select, and the other for polarity. The digital output is provided by a 68HC68P1 chip on the SPI bus. The chip, however,

cannot source enough current to power the coils directly, so a driver circuit is used to provide the necessary current. A simple switching circuit was designed and built to meet this need. However, later it was found that National Semiconductor's LM18293 four channel push-pull driver can perform the same task, so it will be used.

Cost

The magnetic attitude control system was built using off the shelf parts. Less then \$100.00 was spent on material. Coils are wound by using a hand drill. A thin aluminum sheet is used to manufacture the brackets for the coils.

Control Law

The main requirements for the control algorithm are to despin the satellite from arbitrary initial tumbling prior to a picosatellite launch, and to

spin up the satellite to protect it from the thermal radiation of the sun, if necessary. The control system will be used before a picosatellite launch to minimize the satellite's rotation about any axis except the axis of maximum moment of inertia, which corresponds to the picosatellite launch axis. This will guarantee that at the time of a picosatellite launch the picosatellite will have a uniform spin about the launch axis. Once the picosatellite is launched, OPAL will be spun back up to satisfy the thermal requirements. No control is required once the satellite is spinning.

Control Law Description

The control algorithm used to meet these requirements is based on a variation of the well known "minus B-dot" magnetic control law [Reference 1]. This control law works by setting the i^{th} body axis dipole, M_i , according to

$$M_i = -KB_i \quad (i = x_b, y_b, z_b) \quad (1)$$

where \dot{B}_i is the time derivative of the i^{th} body axis component of the geomagnetic field and K is a constant. The \dot{B}_i are obtained directly by differentiating the output of the body mounted magnetometer as follows:

$$\dot{B}_i(t) = [B_i(t) - B_i(t - \Delta t)] / \Delta t \quad (i = x_b, y_b, z_b) \quad (2)$$

where Δt is the sample period. Implementing this control law will despin the satellite from an arbitrary initial tumbling motion and cause the satellite to spin around its maximum moment of inertia axis with a small nutation angle. This control law can also be used to spin up the satellite by reversing the sign on eqn. (1).

Control Law Development

The effect of this control law is to reduce the kinetic energy of the satellite due to rotation about its center of mass. This can be shown through the following development:

The time rate of change of kinetic energy for an arbitrary body due to rotation is given by

$$\frac{d}{dt}(T) = \dot{T} = \underline{\tau} \cdot \underline{\omega} \quad (3)$$

where τ is the external torque acting on the body. The torque on a dipole in a magnetic field is given by

$$\underline{\tau} = \underline{M} \times \underline{B} \quad (4)$$

From a basic theorem of kinematics we have

$$\frac{d}{dt} \text{Inertial} (\underline{B}) = \frac{d}{dt} \text{Body} (\underline{B}) + \underline{\omega} \times \underline{B} \quad (5)$$

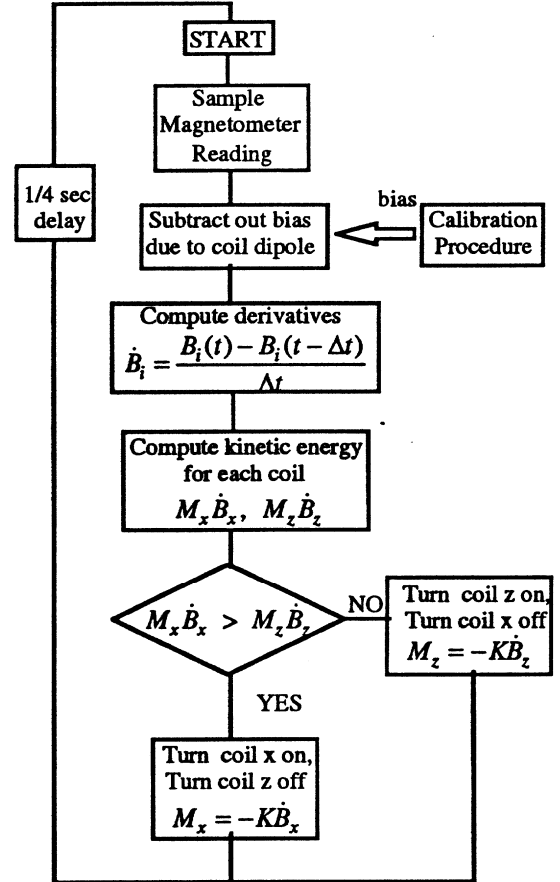


Figure 4. ADC Control Law Flow Chart

Since B , as observed in inertial axes, varies at angular rate $2\omega_o$, we have for $\omega \gg \omega_o$,

$$\begin{aligned} \frac{d}{dt} \text{Inertial} (\underline{B}) &\approx 0 \\ \Rightarrow \frac{d}{dt} \text{Body} (\underline{B}) &= \dot{\underline{B}} \approx -\underline{\omega} \times \underline{B} = \underline{B} \times \underline{\omega} \end{aligned} \quad (6)$$

Combining eqs. (3) through (6), we obtain

$$\dot{T} = \underline{M} \times \underline{B} \cdot \underline{\omega} = \underline{M} \cdot \underline{B} \times \underline{\omega} = \underline{M} \cdot \dot{\underline{B}} \quad (7)$$

Implementing the control law, eqn. (1), we see that

$$\dot{T} = -KB^2 = -K|\underline{B} \times \underline{\omega}|^2 \quad (8)$$

which is clearly less than or equal to zero.

Eqn. (8) shows that we cannot reduce the component of ω along B . This should be clear, since the magnetometer cannot sense this motion, nor can the magnetic coils provide any torque along B . Fortunately, the orbital motion of the satellite ensures that the direction of B does not remain fixed. The net effect of the control law, eqn. (1), is to eliminate all angular motion between the satellite and the B field, resulting in a terminal motion such that the satellite is rotating about its maximum moment of inertia axis with a small nutation angle and aligns the spin axis with the earth's magnetic field.

Control Law Implementation on OPAL

In implementing this control law on OPAL several factors need to be taken into account. These include available power, magnetometer sampling rate, and the number of magnetic coils available. There are two pairs of magnetic coils on OPAL, and due to power constraints only one pair can be on at any one time. The criteria for determining which coil is to be turned on is based upon which coil provides the most kinetic energy loss. A dead-band region was also added in the control to assure the coils are off if no significant motion is detected on OPAL. This guarantees the most efficient use of power for damping out kinetic energy of the satellite. The maximum sampling rate available is four times per second. This sample rate was found to be more than adequate based on computer simulations that will be covered in the next section. Figure 4 shows a flow chart description of the control law implementation on OPAL.

Simulation

Simulations of an earth orbiting satellite were performed to determine the effectiveness of the control law as implemented on OPAL. The simulations assumed a circular orbit. The magnetic field was modeled as a tilted magnetic dipole rotating with the earth based on Wertz (Reference 2). Given these assumptions, simulations are obtained by numerically integrating Euler's equations using Euler parameters as attitude parameters. The input parameters to the simulator are orbit altitude, moment of inertia tensor, magnetic dipole strength of each coil, initial attitude and rates, and the sampling period of the magnetometer.

Several simulations were run to analyze the effectiveness of the control law. The input parameters for each case are given below.

Altitude : 400 (km)
Orbital Period : 92 minute

incination : 30 & 85 degree
Inertia tensor : (in kg m²)

$$\begin{bmatrix} 0.1434 & 0 & 0 \\ 0 & 0.1162 & 0 \\ 0 & 0 & 0.1364 \end{bmatrix}$$

Magnetic moment of the coil :

$$M_x = 1.37 \text{ (A m}^2\text{)}$$

$$M_z = 2.35 \text{ (A m}^2\text{)}$$

Sampling time : 0.25 (sec)

cp-cg offset : [0 0 5] (cm)

Acquisition mode and terminal limit cycle analysis

Time history of angular momentum and angular velocity for acquisition mode with an initial angular velocity of 1 radian per second are plotted in figures 7 and 8. With these initial conditions the satellite can be spun down to within 0.03-0.05 radians per second in approximately one orbit. At this point the satellite reaches a steady state condition that cannot be spun down any more. As can be seen from the figures the only spin rate is along the maximum axis of inertia, which is aligned with the Earth's magnetic field vector. This steady state condition is a terminal limit cycle that is due to the fact that the magnetometer cannot measure the attitude rate along the Earth's magnetic field vector. In eqn. (6), the rate of change of the Earth's magnetic field with respect to inertial coordinate frame was considered small compared to the $\omega \times B$ term and thus neglected in the analysis. However, when the satellite's angular velocity vector gets more closely aligned to the Earth's magnetic field vector, the $\omega \times B$ term becomes very small and the inertial rate term is no longer relatively small compared to $\omega \times B$. By including the inertial rate term, the rate of change of the rotational kinetic energy becomes,

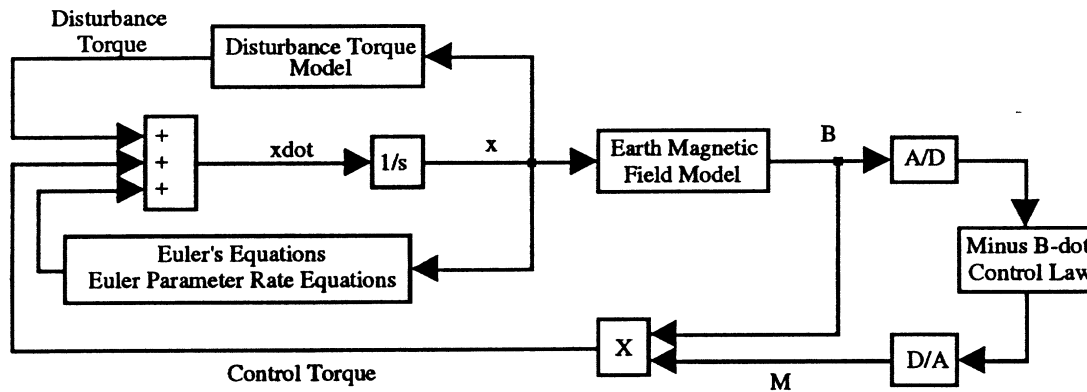
$$\dot{T} = (\underline{M} \times \underline{B}) \cdot \underline{\omega} = \underline{M} \cdot (\dot{\underline{B}}_B - \dot{\underline{B}}_I) \quad (9)$$

With the control law implementation,

$$\dot{T} = -K(\dot{\underline{B}}_B)^2 + K(\dot{\underline{B}}_B \dot{\underline{B}}_I) \quad (10)$$

Eqn. (10) shows that the kinetic energy is not always decreasing. The terminal limit cycle occurs when the first term and the second term of eqn. (10) become equal. If the satellite is tumbling, the minus B-dot law should work as expected. However, once the satellite reaches its steady state condition it will rotate around its major axis, which is aligned with the

Figure 6. Block Diagram of the Simulation



X : State vector containing angular velocity vector and Euler parameters
 M : Control magnetic moment vector
 B : Earth magnetic field vector

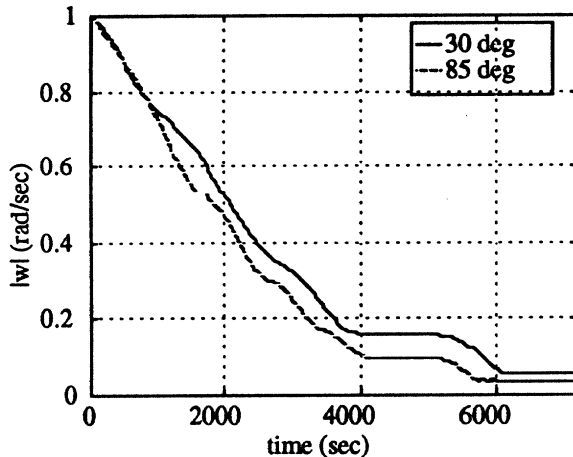


Figure 7. Change in Angular Velocity Over Time

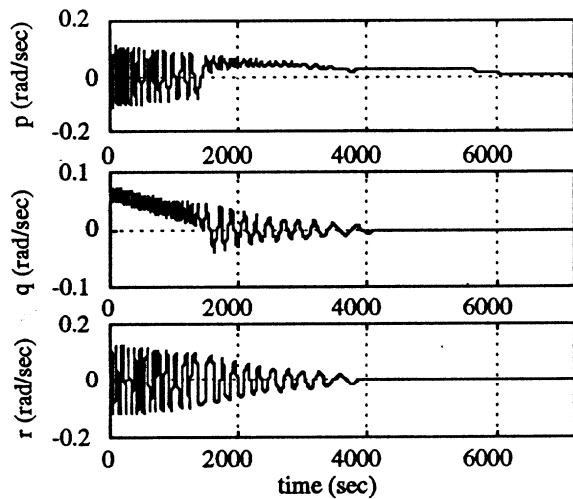


Figure 8. Change in Angular Velocity Over Time, 30 Degree Inclination

earth's magnetic field vector. At this point the inertial rate of the Earth's magnetic field vector starts to have a significant effect on the satellite motion and, eventually, the motion ends up in the terminal limit cycle.

The terminal limit cycle depends on the spin rate of the satellite, the orbit, time and initial conditions because those parameters decide the inertial and body rate of change of earth magnetic field vector. The satellite seems to enter the equilibrium state at approximately 4000 (sec) but, after a while, it moves down another step to reach the final equilibrium state. In this case, the system tried to settle but the spin rate of the satellite was too fast. The spin rate dependency can be intuitively understood through the following explanation. In order to keep the satellite spin axis relatively close to the Earth's magnetic field vector, the spin axis must move with the Earth's magnetic field vector. If the spin rate of the satellite is too fast, the momentum stiffness of the satellite will be so large that the available magnetic control will not be able to maintain the spin axis relatively close to the magnetic field vector. When misalignment occurs the magnetometer will be able to sense the motion and the magnetic control will react to further reduce the spin rate until the momentum stiffness of the satellite and the control torque are in equilibrium. Due to this, the spin rate of the satellite will be small when the limit cycle occurs.

Because this behavior is highly nonlinear and complicated, it is impossible to analyze it analytically but it can be analyzed through simulation. Although this precise analysis is not required for OPAL, analysis may be done for the future use of this control scheme.

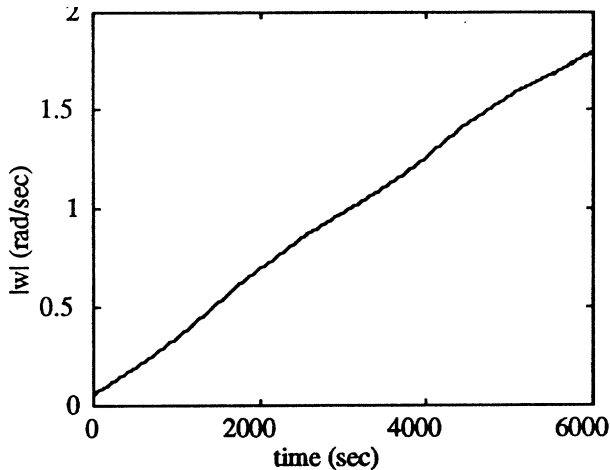


Figure 9 Change in Spin Over Time

Spin up mode

Figure 9 shows that the satellite can be spun up to 1 radian per second in approximately half an orbit. This is much faster compared to the acquisition mode.

Although it is not shown in the figure, once the satellite's spin rate reaches the required value, the control system is turned off and no control is used until the next picosatellite launch.

Possible Error Sources

According to the results of the simulation, the sampling period is small enough relative to the period of the largest possible rotation rate to allow consideration of the effects of having a digital control system such as aliasing, time delay, etc., to be neglected. The time constant of the switching delay due to the inductance of the magnetic coil was calculated to be 0.08 seconds. This is so small compared to the sampling period, which is 0.25 seconds, that it will not add much phase lag to the control loop. There is also an error in the magnetometer reading due to the magnetometer boom flexibility. This flexibility was considered small enough to ignore. The misalignment between the picosatellite launch axis and the maximum axis is ignored, since every effort has been made to align the two axes.

Conclusion

The attitude control requirements for OPAL were met through the application of magnetic control utilizing two air-core magnetic coils and a three axis magnetometer. The control system provides for spin up and spin down modes to meet picosatellite launch requirements and thermal requirements. The control

law used for these modes is based on the simple minus B-dot control law.

Analysis of various operating conditions were examined through computer simulation to determine the effectiveness of this control law. This analysis showed that the motion for a satellite that is tumbling at 1 rad/sec can be dampened to a rotation of 0.05 rad/sec about the maximum axis of inertia in approximately one orbit. It was also found that the satellite can be spun back up from 0.05 rad/sec to 1 rad/sec in approximately half an orbit.

References

[1] Stickler, A. Craig. "An Elementary Magnetic Attitude Control System," Presented at the 1974 AIAA Mechanics and Control of Flight Conference, AIAA Paper No. 74-923.

[2] Wertz, R. James. Spacecraft Attitude Determination and Control, Reidel Publishing Company. Dordrecht, Holland, 1978.

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