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Experimental Assessment of the Influence of Heat Pipes on a Nutating Satellite

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An experimental technique is devised to evaluate the influence of fluid-filled heat pipes on the nutation of a spinning satellite. The technique replicates accurately the acceleration field seen by a heat pipe on a nutating satellite, by mounting the heat pipe on a trifilar pendulum whose characteristics have been designed to produce scaled radial and axial accelerations on the heat pipe at nutation frequency. Scaling theory then allows us to translate the time constant of damped rotational oscillations of the pendulum to nutation-angle growth on the prolate spinning satellite. The influence of air damping in the test setup is allowed for. It is found that the effect of the heat pipes is dominated by energy dissipation due to viscous friction. There is a weak dependence of the time constant upon nutation angle. The time constant reduces with increasing inertia ratio of the satellite. It was difficult to obtain reliable results for inertia ratios greater than 0.9, but consistent results were obtained for all the flight regimes of interest. The results showed that the 13 heat pipes on the satellite had a combined effect on the nutation comparable to that of fuel slosh. Time constants in the range 250–100 s were obtained for the satellite spinning at 60 rpm.

Nomenclature

a_l = axial acceleration on heat pipe, m/s^2
a_r = radial acceleration on heat pipe, m/s^2
E = energy dissipation, J
$\dot{E}$ = energy dissipation rate, J/s
g = acceleration due to gravity, m/s^2
h = rise of pendulum from equilibrium position, m
I = rotational moment of inertia of pendulum, kg m^2
I_T = mean transverse inertia of satellite, kg m^2
l = length of pendulum wires, m
m = mass of pendulum, kg
r = distance of wires from center of rotation, m
r_{hp} = distance of heat pipes from center of rotation, m
α = satellite nutation angle, rad
θ = pendulum rotation angle, rad
σ = inertia ratio of satellite
σ_o = satellite equivalent inertia ratio for other heat pipe
τ_A = time constant due to other effects only, s
τ_{hp} = time constant due to heat pipes only, s
τ_o = time constant of other heat pipe, s
τ_S = time constant of satellite, s
τ_T = time constant of test, s
τ_{TOT} = time constant for heat pipes and other effects, s
ω_N = satellite nutation frequency, Hz
ω_o = satellite spin rate for other heat pipe, Hz
ω_P = pendulum frequency, Hz
ω_S = satellite spin rate, Hz

Introduction

THE second generation of the United Kingdom's military communication Skynet 4 satellites use passive heat pipes to dissipate the heat generated by certain payload units. In transfer orbit, the satellite flies in a spinning mode, and owing to the fact that its mass properties make it a prolate body, active nutation damping is carried out to ensure stability. The assessment of the nutation time constant due to propellant slosh is a well-explored problem and extensively covered in the literature.[1–6] The influence of fluid-filled heat pipes is much less well known, and Ref. 7 is the only paper relevant to the problem that the authors are aware of. It is the purpose of this paper to report on the investigations undertaken to characterize the influence of the fluid-containing heat pipes on the nutation of the spinning satellite.

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Satellite Configuration

The satellite $+Y$ wall, which carries a number of high-heat-dissipating electronics units, is fitted with 13 tubular heat pipes oriented along the satellite's spin axis (the Z axis), and two heat pipes orthogonal to these. About 40% of the internal volume of the heat pipes is filled with ammonia, giving a total mass of ammonia for all the heat pipes of 300 g. The layout of the heat pipes on the Y wall is shown in Fig. 1. The cross section of a heat pipe is shown in Fig. 2.

During transfer orbit, the satellite's mass properties are such that the moment of inertia about its spin axis is less than the moments of inertia about the other two orthogonal axes. Table 1 shows the variation of inertia properties with the mission phase.

Problem

During the early stages of the design there was no awareness that the very small mass of fluid in the heat pipes could significantly influence the nutation characteristics of the satellite. The effects of fuel slosh and associated energy dissipation had already

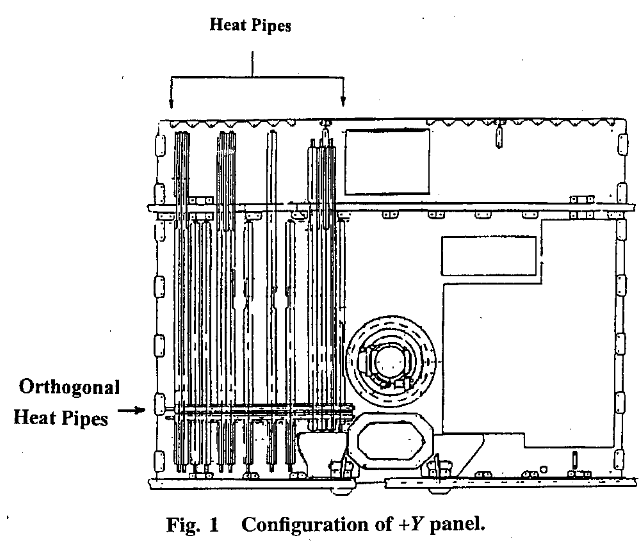

Fig. 1 Configuration of +Y panel.

Table 1 Spacecraft inertia properties

Mission phase	Moments of inertia, kg · m^2 I_{XX}	I_{YY}	I_{ZZ}	Inertia ratio
At separation from launch vehicle	576.0	597.1	504.7	0.86
Prior to apogee boost motor (ABM) burn	574.6	592.7	499.3	0.86
After ABM burn	506.4	524.5	456.9	0.89

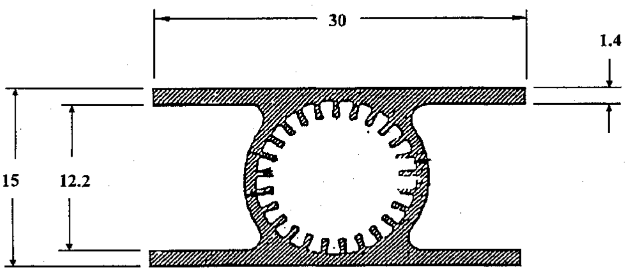

Fig. 2 Cross section of heat pipe. All dimensions are in millimeters.

been investigated experimentally through full-scale tests on an air bearing, and the active nutation damping (AND) system had been designed to provide ample control authority through all relevant mission phases. Nevertheless, an analytic investigation was undertaken as part of the design of the attitude and orbit control system. A search of the literature on the subject yielded a paper[7] that described a very similar problem on the ATS-5 satellite, which is a drum-shaped spin-stabilized satellite with a number of circumferential heat pipes. The authors had treated the problem as one where energy dissipation was through the inelastic impacts of the fluid, acting as a slug, on the heat-pipe end caps. The viscous friction coefficient was treated as a parameter to be evaluated from in-flight measurements. When this parameter was evaluated for one case of the inertia ratio, and the analytic predictions on its basis were generated for other flight cases, agreement with in-flight results was satisfactory.

The same basic approach was therefore adopted for the Skynet 4 investigation, with suitable model modifications to allow for the linear heat-pipe geometry. Since no in-flight results were available for the Skynet 4 case, the value of the viscous friction coefficient was taken to be the same as that determined for ATS-5.

The analytic model yielded very low nutation divergence time constants and indicated a major problem on the satellite. The problem arose in several ways: 1) the fuel required for AND was much greater than the fuel budget had allowed for; and 2) not only would the high AND fuel usage make the attitude determination process subject to greater error, but also the attitude drift between final attitude reconstitution and the firing of the apogee boost motor would result in an inaccurate orbit injection, which would require even more fuel to correct.

Clearly, the problem was such as to require a major rethinking of the design. But before a major redesign was considered, could one be certain that the analytic model, with all its unsubstantiated assumptions, was giving reliable results? It was agreed that independent corroboration, based on a test program, was necessary. The rest of this paper is devoted to a description of a test technique devised to characterize the behavior of the heat pipes in terms of their influence on the spinning satellite.

Nature of the Test

Since the influence of the heat pipes on the satellite's dynamics is directly related to the motion of the contained fluid, the test must recreate accurately the acceleration field to which the flight heat pipe is subjected. The test must also be performed with flight-representative heat pipes. In flight, the heat pipe experiences a radial acceleration owing to the satellite's spin rate, and an axial acceleration owing to the nutation. The latter is essentially sinusoidal with a period equal to the nutation period, while the former can be considered to be constant.

It is possible to create an acceleration field of this nature by mounting the flight heat pipes on a trifilar (torsional) pendulum. The acceleration due to gravity provides the radial acceleration, while the pendulum motion provides the sinusoidal axial acceleration. The pendulum's period is, of course, the satellite's nutation period.

We set up the pendulum to mimic the satellite acceleration field, nutation period, and inertia ratio, and observe the history of the damped torsional oscillations. The damping is due to two effects: 1) the aerodynamic drag of the pendulum and the heat pipes and 2) the fluid motion within the heat pipes.

The first effect is isolated by performing the test with dummy heat pipes, i.e., heat pipes devoid of the working fluid. The damping effect of the fluid alone is then translated from the pendulum to the satellite through the scaling laws outlined in the next section.

Scaling Laws

For a nutation angle of 1 deg and a spin rate of 60 rpm, the on-orbit satellite with an inertia ratio of 0.86 would impose the following accelerations on the heat pipe closest to the spin axis: a radial acceleration of 2.8 g, and a peak axial acceleration of 0.41 m/s^2. In the test, the force of gravity provides the radial acceleration. Since this is 1 g instead of 2.8 g, this ratio provides the scaling factor for the axial acceleration. In fact, the test replicates the on-orbit condition of the satellite spinning at a rate that results in a 1 g radial acceleration. The period of the pendulum must therefore be equal to the nutation frequency corresponding to this reduced spin rate and to the satellite's inertia ratio. Once we have translated the test results to on-orbit behavior, we scale to 60 rpm using the well-established relationship for energy-dissipation-dominated nutation behavior[3]:

$$\omega_S \tau_S = \text{constant} \tag{1}$$

Throughout this analysis, we use the concept of a time constant, implying that the nutation behavior is dominated by the mechanism of viscous energy dissipation and will consequently show exponential variation with time. Implicit in this assumption is that the time constant is independent of the nutation angle. Within this context, much previous work has shown that the relationship $\omega_S \tau_S$ = constant holds to good accuracy.

We now show how the test measurement, which is a time constant associated with the decay of torsional oscillations of the pendulum, is related to the nutation behavior of the satellite.

The energy equation of a trifilar pendulum can be written as

$$E = \tfrac{1}{2} I \dot{\theta}^2 + mgh \tag{2}$$

For small θ, simple geometry gives us $h = (r\theta)^2/2l$. We have, therefore,

$$E = \frac{1}{2} I \dot{\theta}^2 + \frac{1}{2} \frac{mg(r\theta)^2}{l} \tag{3}$$

The energy dissipation rate $\dot{E}$ is given by

$$\dot{E} = I \dot{\theta} \ddot{\theta} + mg(r^2/l)\theta\dot{\theta} \tag{4}$$

Assuming that the variation of θ is of the form $\theta = \theta_0 \exp(-t/\tau_T)$,

$$\dot{E} = -\frac{I\theta^2}{\tau_T^3} - \frac{mg(r\theta)^2}{l\tau_T} \tag{5}$$

$$\dot{E}/\theta^2 = -\left(I/\tau_T^3\right) - \left(mgr^2/l\tau_T\right) \tag{6}$$

For the spacecraft inflight, we have the relationship

$$\frac{\dot{E}}{\alpha^2} = -\frac{I_T \omega_S^2 \sigma(\sigma - 1)}{\tau_S} \tag{7}$$

With τ_T measured during the test with the trifilar pendulum, we need a relationship between $\dot{E}/\theta^2$ and $\dot{E}/\alpha^2$ to be able to derive τ_S. We have, therefore,

$$\dot{E}/\alpha^2 = (\dot{E}/\theta^2) \cdot (\theta^2/\alpha^2) \tag{8}$$

Table 2 Variation of time constant with inertia ratio

Inertia ratio	Time constant, s
0.805	7400
0.865	5200
0.886	3500

The relationship between θ and α is derived as follows. For the satellite, the axial and radial accelerations on the heat pipe are related by

$$a_l = a_T \sigma \tan\alpha \tag{9}$$

For the test rig, the axial acceleration on the heat pipe is given by

$$a_l = -\ddot{\theta} r_{\text{hp}} \tag{10}$$

The radial acceleration is simulated by the acceleration due to gravity. The scaled axial acceleration is therefore

$$-\ddot{\theta} r_{\text{hp}} = g\sigma \tan\alpha \tag{11}$$

For the rig, $\ddot{\theta} = -\omega_P^2 \theta$. We have, therefore,

$$\omega_P^2 \theta r_{\text{hp}} = g\sigma \tan\alpha \tag{12}$$

Since ω_P is set to the nutation frequency of the satellite, we have

$$\omega_P = (1 - \sigma)\omega_S \tag{13}$$

and therefore

$$\theta = \frac{\sigma g \tan\alpha}{r_{\text{hp}}(1 - \sigma)^2 \omega_S^2} \tag{14}$$

To ensure that we obtain $\dot{E}$ only due to the liquid in the heat pipe, we need to do a test with the heat pipe replaced by a dummy without fluid, and determine the resulting τ. We then use the relationship below to determine the influence of the heat pipe on its own:

$$1/\tau_{\text{hp}} = (1/\tau_{\text{TOT}}) - (1/\tau_A) \tag{15}$$

We derive the contribution of the other heat pipes on the satellite from the test result on the tested heat pipe by deriving the equivalent spin rate and inertia ratio, and scaling up to flight conditions, as follows. The equivalent spin rate for another heat pipe, ω_o, is that which would produce the same acceleration field as seen in the test. In addition, because the period of the trifilar pendulum is determined by test conditions, the equivalent satellite inertia ratio for the other heat pipe, σ_o, is given by knowledge of the equivalent spin rate and the measured pendulum period (which is the satellite nutation period, ω_N). We have

$$\sigma_o = 1 - (\omega_N/\omega_o) \tag{16}$$

The time constant for the other heat pipe is given by

$$\tau_o = \frac{I_T \omega_o^2 \sigma_o (1 - \sigma_o)}{\dot{E}/\alpha_o^2} \tag{17}$$

But $\dot{E}/\alpha_o^2$ is unknown, whereas we have evaluated $\dot{E}/\alpha^2$ for the tested heat pipe through the measurement of $\dot{E}/\theta^2$ and Eq. (8). We can evaluate $\dot{E}/\alpha_o^2$ from $\dot{E}/\theta^2$ as follows:

$$\frac{\dot{E}}{\alpha_o^2} = \frac{\dot{E}}{\theta^2}\frac{g}{r_{\text{hp}}}\frac{\sigma_o^2}{(1 - \sigma_o)^4}\frac{1}{\omega_o^4} \tag{18}$$

Expressing $\dot{E}/\alpha_o^2$ in terms of $\dot{E}/\alpha^2$, we have

$$\dot{E}/\alpha_o^2 = (\dot{E}/\alpha^2)(\sigma_o/\sigma)^2[(1 - \sigma)/(1 - \sigma_o)]^4(\omega_S/\omega_o)^4 \tag{19}$$

Substituting Eq. (18) into Eq. (17) and using the expression for τ_S from Eq. (7), we can write the time constant of the other heat pipe as

$$\tau_o = \tau_S(\sigma/\sigma_o)[(1 - \sigma_o)/(1 - \sigma)]^5(\omega_o/\omega_S)^6 \tag{20}$$

Once τ_o is known, we need to relate it to the spacecraft through a relationship between the time constant and the inertia ratio, other things being constant. Our tests have been carried out for four different inertia ratios, but the test for the inertia ratio closest to unity gave unreliable results owing to the pendulum's rotational instability. Restricting ourselves, therefore, to inertia-ratio values of 0.806, 0.865, and 0.886, we have the variation shown in Table 2. This table shows the variation with inertia ratio of the time constant of a single heat pipe measured during test. We use this relationship to convert the other heat-pipe time constants to the single inertia ratio of the satellite.

The total time constant of the satellite, due to all the 13 heat pipes, is then obtained from

$$1/\tau_S = (1/\tau_1) + (1/\tau_2) + (1/\tau_3) + \cdots + (1/\tau_{13}) \tag{21}$$

Test Setup

The design of the details of the test setup was governed largely by the need to produce results as quickly as possible. The satellite was in the early build stage, and any modifications required had to be identified as soon as possible. The test setup closely resembled the illustration in Fig. 3. The pendulum parameters were chosen so that the tests could encompass the range of inertia ratios and nutation angles encountered in flight. Pendulum constraints allowed rotation angles corresponding to in-flight nutation angles of 2 deg or less.

The main difficulty experienced with the apparatus was associated with setting up the initial rotation angle in such a way that subsequent release resulted in a purely rotational motion. Corruption of this motion had to be kept to very low levels if the behavior of the fluid in the heat pipes was to replicate in-orbit conditions. To achieve this, the pendulum was held at the required initial displacement by a friction plate applied to the underside. Concentricity was ensured

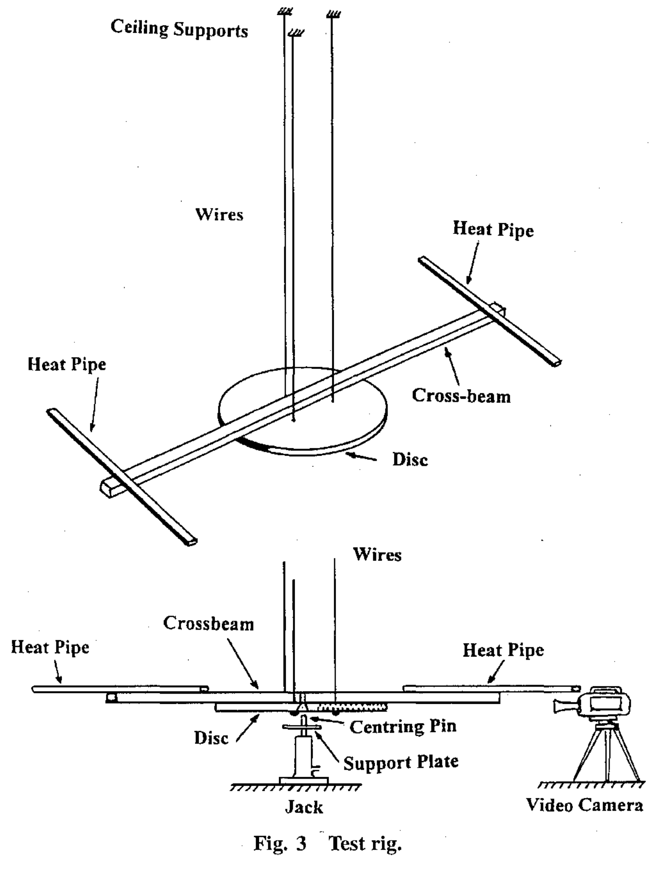

Fig. 3 Test rig.

Table 3 Test-rig parameters

Pendulum length	3 m ± 0.5 mm			
Pendulum mass	28.75 ± 0.01 kg			
Pendulum rotational inertia	12.05 kg · m^2			
Mounting radius of heat pipes	1.95 m ± 0.2 mm			
Satellite inertia ratio	0.806	0.865	0.886	0.905
Suspension-wire distance from center, m	0.250	0.175	0.147	0.125
Rotation angle for 1-deg nutation on satellite, deg	8.0	17.25	25.0	32.0
Pendulum period, s	9.0	12.85	15.3	18.0

Table 4 Satellite time constants due to heat pipes

Inertia ratio	Time constant, s	Rotation angle, deg	Nutation angle, deg
0.806	235	15 to 4	1.9 to 0.5
0.806	238	8.5 to 3	1.1 to 0.4
0.806	233	5.5 to 3	0.7 to 0.4
0.865	184	10 to 2	0.6 to 0.1
0.865	214	10 to 6	0.6 to 0.4
0.865	169	6 to 2	0.4 to 0.1
0.886	207	29 to 8	0.9 to 0.25
0.886	105	19 to 8	0.6 to 0.25
0.886	85	10 to 5	0.3 to 0.16

by visually checking from above the clearance between a vertical central pin on the friction plate and an oversize (4-mm diam) central hole in the pendulum. Pre-tension in the pendulum wires was maximized to avoid an initial shock on release. The release was controlled by a pneumatic piston choked to an appropriate speed to ensure a clean, shock-free release.

To avoid pooling of the fluid within the heat pipes, great care was taken to ensure that the heat pipes, as well as the rotational motion, were in the horizontal plane. The measurement of the rotational decay was achieved by a video-camera record of a scale edge-mounted on the pendulum disk. A record of the time was also captured within the frame of the video camera. The frame rate was 25 frames/s, and the accuracy with which the angle scale could be read was 0.125 deg. A freeze-frame analysis allowed the time history of rotation-angle peaks to be extracted to better than 3% accuracy.

The test rig parameters are shown in Table 3.

Results

Tests were carried out for four satellite inertia ratios. The highest, 0.905, did not give consistent results, largely owing to the difficulty of ensuring concentric motion. We will therefore only discuss the results for the inertia ratios 0.806, 0.865, and 0.886. The inertia ratio 0.865 represents the spacecraft prior to activation of its solid-propellant apogee boost motor, and 0.886 represents the satellite after apogee motor burnout.

Table 4 shows the time constants, on the satellite spinning at 60 rpm, of nutation divergence due to all 13 heat pipes. A distinct but weak dependence on the nutation angle can be seen. Figures 4 and 5 show traces of the rotation angle vs time for the active and dummy heat pipes; Figs. 6 and 7 show the variation of $-\ln(\theta/\theta_0)$ vs time for the same cases. If the time constant were independent of rotation angle, the latter traces would be straight lines. It is clearly seen that there is only a weak dependence on rotation angle. These traces are typical for all the results shown in Table 4. During the test program, each test was run twice and only accepted if the two runs showed closely similar results. Repeatability of better than 5% was achieved.

From the results the main conclusions are as follows: 1) exponential decay behavior, necessary if the concept of a time constant is to be meaningful, is indeed observed; 2) both the dummy and the active heat pipes show this behavior, and hence the isolation of the effect of the fluid alone can be achieved as previously outlined; 3) the main mechanism of fluid behavior is that of viscous energy dissipation and not of fluid slugs impacting the tube ends; 4) there is a substantial dependence of time constant upon inertia ratio, as

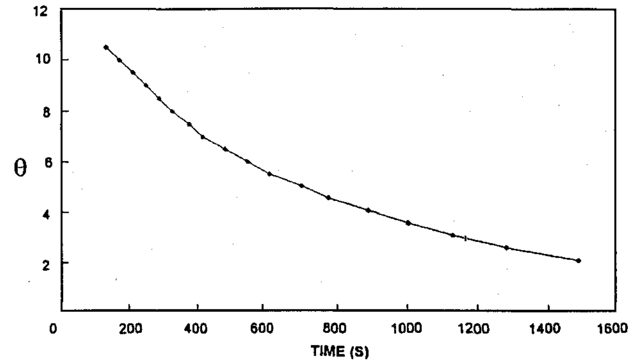

Fig. 4 Active-heat-pipe rotation angle vs time (inertia ratio 0.865).

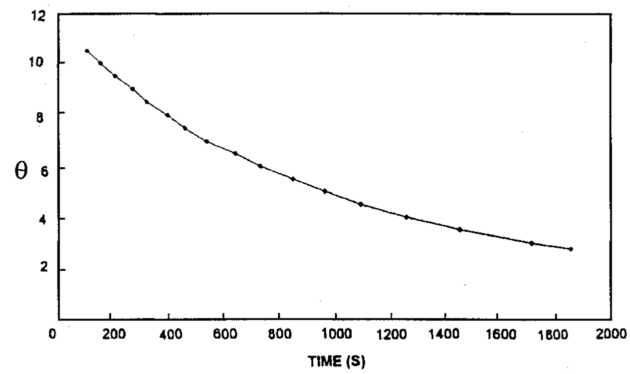

Fig. 5 Dummy-heat pipe rotation angle vs time (inertia ratio 0.865).

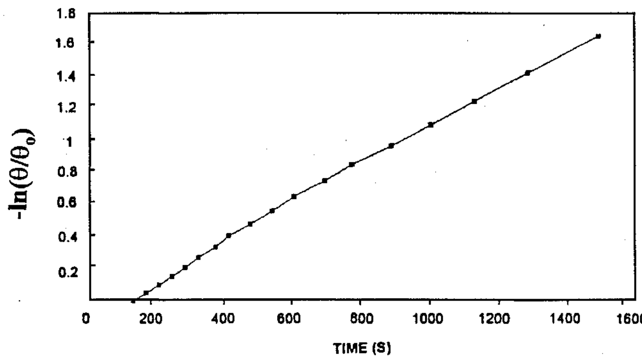

Fig. 6 $-\ln(\theta/\theta_0)$ vs time for active heat pipe (inertia ratio 0.865).

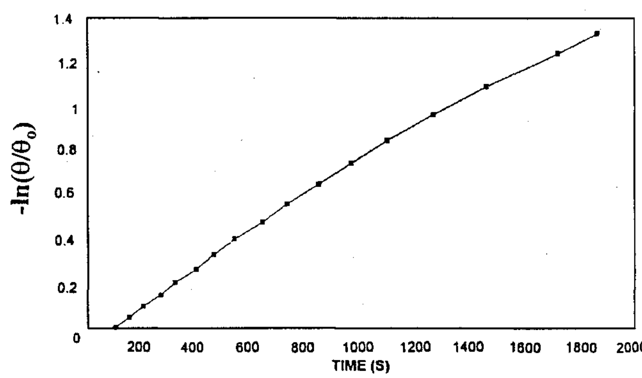

Fig. 7 $-\ln(\theta/\theta_0)$ vs time for dummy heat pipe (inertia ratio = 0.865).

shown in Fig. 8; and 5) there is a weak dependence of time constant upon nutation angle.

This implies that the mechanism, though largely one of viscous energy dissipation, also includes some features of the fluid impacting the tube ends. To investigate this further, flow visualization tests were carried out with transparent tubes of representative length and bore (though without the internal vanes) containing fluid of similar density and viscosity. The fluid was seen to move gently from end to end of the tube over a complete pendulum cycle. On reaching

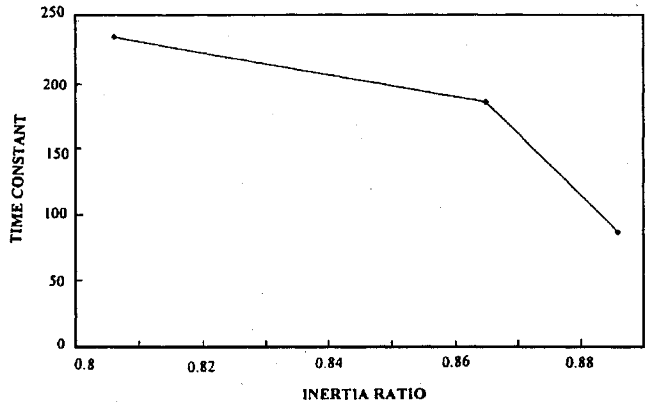

Fig. 8 Variation of satellite time constant with inertia ratio.

the ends, the fluid was reflected, and briefly, a compression wave was set up by the action of the oncoming and reflecting fluid. No sluglike behavior was seen.

Conclusions

When coupled with the effect of propellant slosh, the effect of the heat pipes gave nutation divergence time constants sufficiently low to have an unacceptable effect on the mission. It was therefore decided to modify the thermal design to eliminate the heat pipes altogether. Though this is the best solution from a satellite mission point of view, it means that there will, sadly, be no opportunity to validate these predictions through in-flight measurements.

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