AN EXPERIMENTAL INVESTIGATION OF SPACECRAFT SLOSHING

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ABSTRACT

Slosh testing of the Eurostar spacecraft is described. The spacecraft contains about 1 tonne of propellants on board, and these have a significant influence upon its dynamic characteristics. To define these, an extensive series of drop tests was undertaken. The nutation time constant was the principal parameter of interest. The testing involved dynamical scaling, model fabrication and all data capture and analysis. Initial tests indicated very short time constants and corrective action was necessary. This involved designing internal baffles to modify the fluid motion.

Keywords: Spacecraft Nutation, Propellant Slosh, Drop Tests, Baffle Design.

1. INTRODUCTION

With the trend towards increasing use of liquid bi-propellant propulsion systems on board spacecraft, it has become necessary to understand and characterise the influence of bulk fluids on rigid body dynamics. This paper describes the experimental test programme undertaken to characterise the rigid body dynamics of the Eurostar spacecraft during the Parking and Transfer Orbit phases of the mission, during which the spacecraft is spin stabilised.

The Eurostar spacecraft employs a liquid bi-propellant propulsion system for the apogee manoeuvre in addition to all attitude and orbit adjust manoeuvres. It can, therefore, carry about a tonne of propellants on board constituting about 55% of the total spacecraft mass in Transfer Orbit. This propellant it carries in four tanks symmetrically disposed about, but offset from, the spin axis, Fig. 1. The spacecraft is designed to spin about an axis of maximum inertia, and to have an inertia ratio (defined as the ratio of spin inertia to maximum transverse inertia) sufficiently greater than unity to ensure spin stability even in the face of re-locatable fluid masses on board. In Parking Orbit, however, when the spacecraft is attached to its Pam-DII upper stage for Shuttle launch, the stack is prolate (i.e. the inertia ratio is less than unity) and hence unstable about the spin axis. Active control is, therefore, undertaken to ensure stability during this phase of the mission. The active control is accomplished by the active nutation damper on the spacecraft.

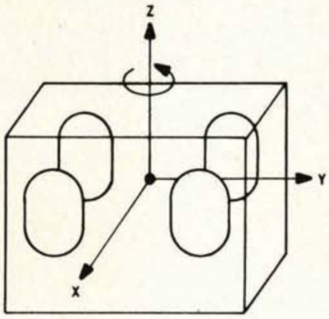

Fig. 1

A parameter of critical importance in the design of the AND, and in the design of the mission sequence is the time constant of divergent nutation. This expresses the rate of increase of body nutation owing to energy dissipation in the body - contributed primarily by the fluid motion within the tanks. The time constant is defined by the expression

$$\theta = \theta_0 \exp (t/\tau)$$

where θ is the instantaneous nutation angle, θ_0 is the initial nutation angle, t is the current time, and τ is the time constant. It can be seen that in the elapsed time, t, equal to the time constant, τ, the nutation angle has increased by a factor e(= 2.71828).

2. STABILITY IN PARKING ORBIT

Let us now see why the time constant is such an important design parameter during the parking orbit phase of the mission.

As mentioned above, when the spacecraft is attached to its upper stage, the spinning stack is prolate and therefore unstable in the face of non-zero energy dissipation. If uncontrolled, the stack will begin to nutate and the nutation angle will increase until it reaches a value of 90°, when the stack is said to be in a "flat spin", spinning about its maximum inertia axis. See Fig. 2. This effectively means loss of the mission because the perigee

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motor will not be pointing in such a way as to enable it to deliver the desired propulsive impulse to the spacecraft. To avoid this situation active nutation control is instituted. This effectively counteracts the natural growth of the nutation angle and maintains the stack spinning about the minimum inertia axis.

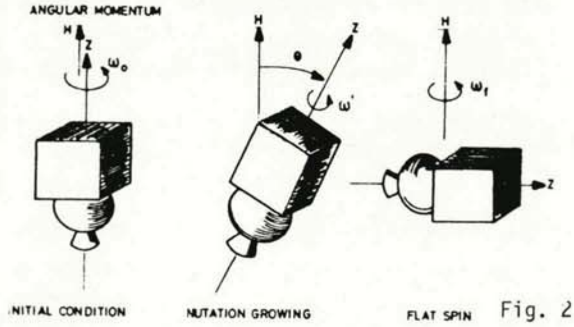

Fig. 2

To ensure the safety of the Orbiter and its crew, deployed payloads are prohibited from using their thrusters until they are outside a safety boundary around the Orbiter. The distance of this boundary around the Orbiter depends upon the nature of the thruster and can shrink to zero for small cold-gas thrusters. For hot-gas thrusters commonly used on spacecraft, however, this safety boundary is about 200 ft from the Orbiter, though this distance is negotiated by NASA on a case-by-case basis.

Most spin-stabilised payloads are spring-ejected from the cargo bay, and therefore have a finite separation velocity. This is of the order of 1 to 2 ft/s. It can be seen, therefore, that there exists a period of about 100 s after deployment from the cargo bay during which thruster separation is forbidden. If the spacecraft's active nutation controller is based on thruster actuation (as most are) this period is effectively 'dead time' for such a system. The nutation of the stack will, therefore, have grown to some finite value before the controller can begin to counteract it. The uncontrolled growth of the nutation angle depends upon the initial nutation angle and the time constant of nutation angle divergence. The former depends upon stack inertia characteristics and deployment system asymmetries, the latter depends largely upon the rate of energy dissipation within the stack. The greater the energy dissipation, the lower the time constant, and the faster the nutation angle increases.

Design of the active nutation damper requires a good estimate of the time constant of divergent nutation, and it is in the prediction of this parameter that substantial difficulty arises. It is not possible to predict this parameter by analytic means alone. Extensive testing has to be resorted to, to characterise this parameter with suitable accuracy for the full range of conditions encountered in flight.

The test programme undertaken for Eurostar is described below.

3. OBJECTIVES OF THE TEST PROGRAMME

The prime objectives of the test programme were the following:

- to allow an adequate characterisation of the nutation time constant during the Parking Orbit phase of the mission, i.e. prior to upper stage burn;
- to obtain an adequate characterisation of the nutation time constant after the upper stage burn and before the spacecraft separates from the upper stage;
- to include parameter variations to envelope all possible flight conditions.

Subsidiary objectives were:

- testing should be cost effective
- testing is required to be completed within a short timescale to support hardware design and definition;
- the test house should provide quick response and high flexibility in response to test findings.

4. SELECTION OF TEST METHOD

Several test techniques are available. These are-

- air bearing test
- drop test
- test within an aircraft flying a zero-gravity trajectory
- spin-table/gimnal tests

Of the above, the most used for spacecraft testing are the air-bearing test and the drop test.

It was decided that from a technical standpoint only the air-bearing and the drop test methods would give satisfactory accuracy with an affordable input of effort. Hence the following test authorities were approached:

- Intespace - air bearing tests
- NASA (Goddard Space Flight Centre)/ Astrotech - air bearing tests
- Ford Aerospace - drop tests
- Applied Dynamics Labs. - drop tests.

From a cost and schedule point of view it became clear that the air bearing method could not compete with the drop-test method. The latter was seen as the most cost-effective. The final choice fell on Applied Dynamics Labs. owing to considerations of cost, response flexibility, and technical confidence.

5. DESCRIPTION OF TEST FACILITY

The drop test facility is purpose built and allows a maximum drop height of 11 m. Among the special features are a high ceiling and adequate lighting for viewing and filming the drop tests. The facility consists of the following hardware:

- spin-up and release mechanism (illustrated in Fig. 3);
- tower and catch box (illustrated in Fig. 4);
- telemetry and data processing system (illustrated in Fig. 5).

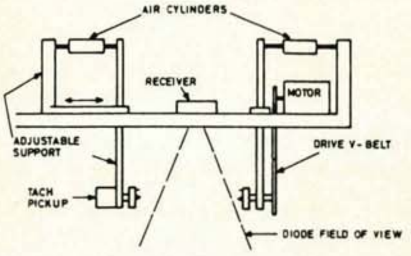

Fig. 3

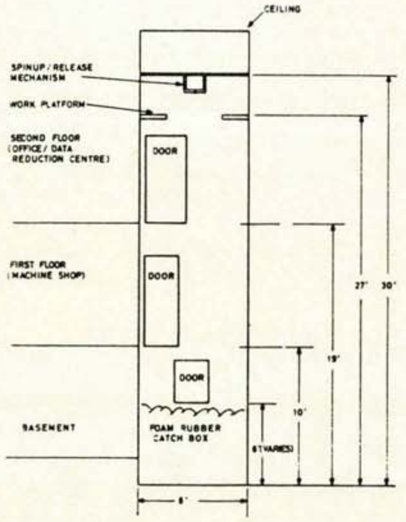

Fig. 4

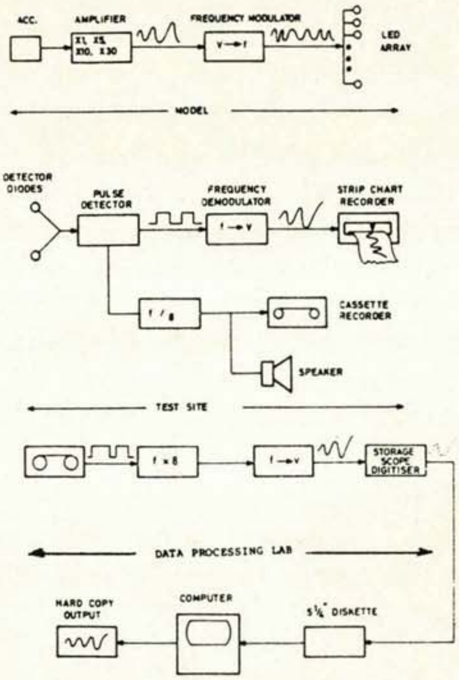

Fig. 5

The spin-up and release mechanism is used to spin the model to a desired speed, sense the speed, and release it on command. It also serves as a mounting point for the telemetry receiver. The model is supported by two pivoting arms whose position is controlled by pneumatic cylinders. A bearing-mounted shaft on each arm provides non-slip engagement with the model. One shaft is driven through a V-belt by a 3/4-HP constant-torque variable-speed motor. The other shaft drives a tachometer sensor for measuring the model rotation rate. The height of the mechanism above the foam rubber in the catch box gives a drop time of just over 1 second.

The tower and catch box serve three main purposes. They provide for the loading of the model into the spin-up and release mechanism, the viewing of the model in free fall, and the undamaged recovery of the model. The last is accomplished with pieces of foam rubber which dissipate the rotational and translational energy of the model without inducing excessive stress within it.

The telemetry and data processing system is shown in Fig. 5, and consists of:

- a single-axis accelerometer,
- an infra-red telemetry system,
- a magnetic tape recorder,
- an analog strip chart recorder,
- a computer-controlled data processing system.

The accelerometer is a standard piezo-electric transducer with an internal charge amplifier, a 5000 Hz bandwidth, and a resonance frequency of 40000 Hz. The acceleration measured by the accelerometer in the model and the model's nutation angle are related by the following expression

$$\theta = \tan^{-1}\left[\frac{A}{\lambda(2-\lambda)r\,\omega^2}\right]$$

where θ is the nutation angle, A is the accelerometer output, λ is the inertia ratio, r is the radial distance the accelerometer from the spin axis, and ω is the spin rate.

The infra-red telemetry system was chosen because of its inherent simplicity when operated in pulse-width modulation mode. The optical transducer is a light-emitting diode (LED) array, and is mounted around the periphery of the model, about the axis of rotation. Since each LED emits light on a broad beam there are no transmitter-receiver alignment problems.

The receiver is mounted on the spin-up and release mechanism, directly over the spinning model. It generates two signals, one is analogue, and is proportional to the output of the accelerometer in the model. The strip-chart recorder monitors this signal to provide immediate visual evidence of the quality of the drop. The other signal is the frequency modulated carrier received from the model. This is recorded on the tape recorder for analysis by the computer.

The data processing system incorporates an analogue-to-digital converter, and data storage and reduction routines. The data from the tests are stored on $5\frac{1}{4}$ inch magnetic diskettes.

6. TEST PROCEDURE

The test procedure is a very simple one and consists of the following steps:

- The model is adjusted for the particular drop being performed. The adjustment would, typically, consist of setting up the correct inertia ratio, fill fraction, and amplifier gain.
- The model is mounted in the spin-up and release mechanism, and secure mounting is verified
- The telemetry link is established and verified
- The recording equipment is initialised
- The model is released, and drops into the foam-filled catch box
- The quick-look data analysis is carried out to obtain the approximate time constant and nutation frequency
- The model is retrieved from the catch box and prepared for the next drop.

Detailed, computer-supported, analysis of the output trace takes place off-line, and provides more accurate estimates of the parameters of interest. Parts of the trace can be selectively "windowed" and analysed separately in order to obtain accurate results.

7. ACCURACY

The most stringent assessment of the accuracy of a test technique is how well the test results compare with in-flight hebaviour. For the drop test method two such comparison cases are available. Both on the INSAT-1A spacecraft launched on 10 April 1982. Details of the comparison are available in Ref. 1, here we shall summarise the results.

The two cases are:

(a) Just before separation from the Delta second stage.

(b) After burnout of the Delta PAM stage.

For the second case, (b), testing predicted a time constant of 29s for nutation angles less than 8°. The in-flight measurement indicated a time constant pg 22 ± 3s with nutation angles from 17° to 30°. Thus, neglecting any dependence of the time constant on nutation angle, the drop test prediction is accurate to 13%.

For the first case (a), the in-flight measurement has a small signal-to-noise ratio and much processing (digital filtering) was necessary to extract the time constant, the average value of which was found to be 69.5s. The drop test prediction is 85s, giving a prediction accuracy of 22%.

A prediction accuracy of about 20% is considered excellent for nutation divergence predictions, and certainly suffices to enable spacecraft mission design to proceed with good confidence.

8. MODEL SCALING

For the drop test results to be properly representative of the flight situation, the model must be carefully scaled with respect to several dynamical and fluid motion parameters. The table below shows which parameters need to be scaled and which parameters need to be identical between the spacecraft and the model.

The first step in the scaling procedure is the choice of the liquids to represent the fuel and oxidiser of the spacecraft's propulsion system. For the test reported here, water was used to represent Monomethylhydrazine (MMH), and chloroform was used to represent Nitrogen Tetroxide (NTO).

In order to obtain a close Reynolds Number match with the selected fluids, a length scale of 6.56 : 1, and a time scale of 42.2 : 1, were used. Here it suffices to say that for both the pre- and post- PAM burn cases investigated, a well-scaled model resulted. The main characteristics of both models are shown in Table 2.

The model and propellant tank are illustrated in Figs. 6 and 7. Aluminium was used throughout, except for pieces designed to create planned variations in inertia ratio. These were of lead and steel. The model was clad in an expanded polystyrene material, to present a smooth exterior to the foam in the catch-box.

THE DROP TEST MODEL

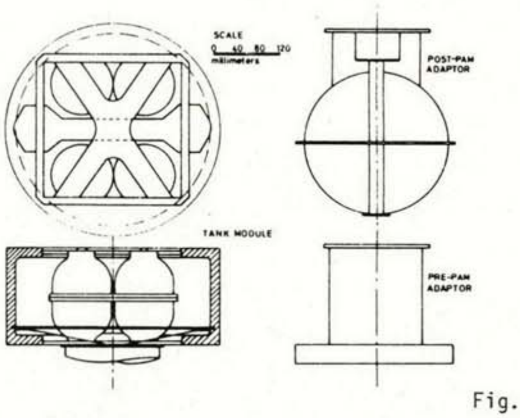

Fig. 6

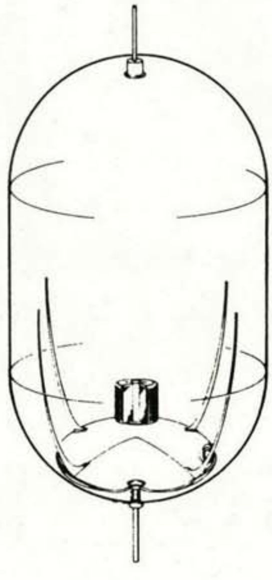

Fig. 7

Table 1.

Parameter	Scaled	Identical
Inertia about principal axes	✓	
Inertia ratio		✓
Mass	✓	
Dimensions of tank, tank location, PMD, model c.g	✓	
PMD vane modulus of elasticity	✓	
PMD vane density	✓	
Liquids : density, kinematic viscosity	✓	
Spin rate, time	✓	
Ratio of liquid-to-system mass		✓
Ratio of liquid-to-system spin inertia		✓
Tank fill fraction		✓
Reynolds Number		✓
Froude Number	greater than about 10	
PMD deflection due to liquid motion		✓
PMD deflection due to spin field		✓
<u>Note</u> : PMD is Propellant Management Device		

Table 2.

Pre-PAM Case		Model	Spacecraft
Mass	(kg)	20.5	5214
I_{xx}	(kgm²)	0.44	4766
I_{yy}	(")	0.45	4871
I_{zz}	(")	0.2	2143
I_{xy}	(")	0.0055	59.6
Fraction fill		0.89	0.89

Post-PAM Case		Model	Spacecraft
Mass	(kg)	9.7	2133
I_{xx}	(kgm²)	0.19	1902
I_{yy}	(")	0.20	2009
I_{zz}	(")	0.12	1244
I_{xy}	(")	0.0054	59.6
Fraction fill		0.89	0.89

9. PRELIMINARY TEST RESULTS

Before the testing started a test programme was established, incorporating the appropriate parameter variations to envelope all the flight cases of interest. The parameters that were varied were:

- the inertia ratio;
- the fluid fill fraction in the tanks;
- the spin speed.

However, preliminary drop tests to check out the operation of all the hardware indicated alarmingly low time constants, considerably shorter than expected. These early drops indicated time constants in the region of 24s and 33s at 30 rpm for the pre- and post- PAM configurations respectively.

The test programme drawn up initially was therefore, abandoned and the testing was redirected towards understanding the cause of the very short time constants that were being measured. Various causes were postulated:

- high energy dissipation unrelated to fluid motion:
- high energy dissipation due to influence of the propellant management device (PMD);
- high energy dissipation due to influence of PMD sponge;
- fluid resonance;
- transient fluid motion at the instant of release.

The first hypothesis was quickly dismissed by carrying out a drop with empty tanks and observing that the body nutation angle was virtually constant during the free fall period. The fluid was therefore responsible for the short time constants, but through what mechanism was far from clear.

Next, the last phyothesis was investigated by allowing various settling times at the desired test rotation rate before release of the model. For very short settling times, i.e. 1 to 5 s, repeatable results could not be obtained. For settling times greater than 10s or so repeatable results were obtained, but the short time constants persisted.

A series of tests was then performed to assess the influence of the PMD. This was done by removing the PMD from the tanks and repeating the tests. The time constants for both configurations approximately doubled. It was clear that the PMD was having some influence on the fluid and this was most probably due to the slender and flexible vanes, rather than the sponge as further tests confirmed.

These tests gave more information but did not point to a solution to the problem, as deletion of the PMD was not a viable design option.

This left one mechanism to account for the measured behaviour - some sort of fluid resonance or bulk motion. The tests reported in the next section were carried out to throw some light on this hypothesis.

10. MAIN TEST PROGRAMME

For both the pre- and post- PAM configurations sweeps were made, in turn, of the inertia ratio, the fill fraction, and the spin speed.

Variation in the spin speed over all the tests indicated that for any fixed set of conditions the time constant varied inversely as the spin speed. The relation

$$\omega\tau = \text{constant}$$

held to within 10% accuracy.

The effect of varying fill fraction and inertia ratio is shown in Figs. 8 and 9 for the pre- and post- PAM configurations. It can be seen that the effect of fill fraction variation was very different for the two configurations. Within the limited range of inertia ratio variations explored, no strong trend was evident. What all the tests did indicate was that the low time constants persisted throughout the range of parameter variations explored. If fluid mode resonance was responsible, it certainly was not a sharply defined effect that could be unlocked by significant changes in fill fraction and inertia ratio.

The only mechanism left, which could account for the low time constants, seemed to be bulk motion of the fluid, but of what nature remained unknown.

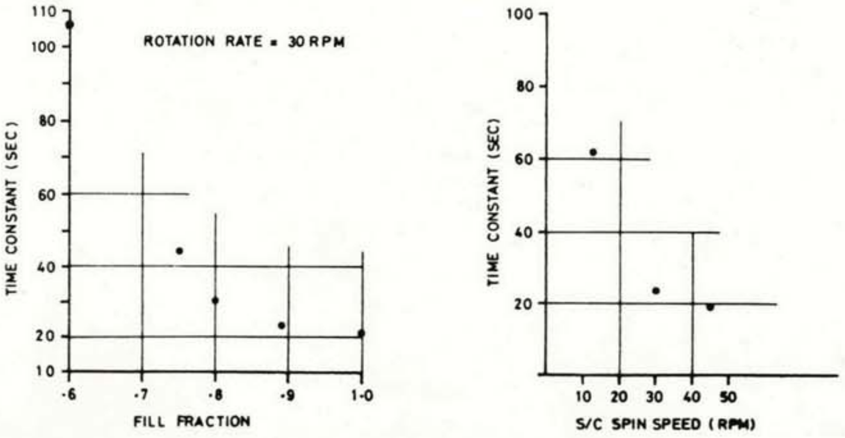

Fig. 8

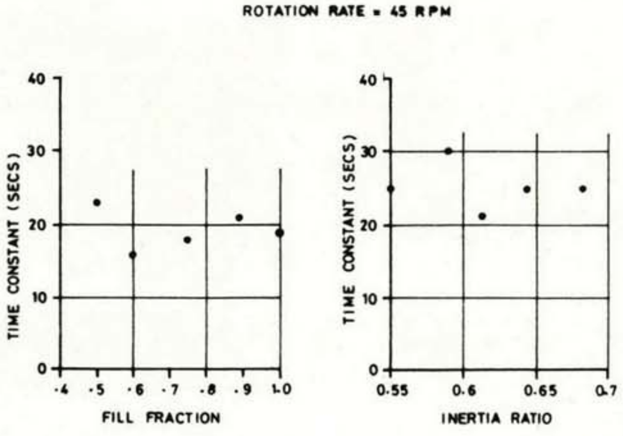

Fig. 9

It was very clear that the time constants measured were not acceptable as far as mission design was concerned. What were the alternatives? They are:

1) avoid use of STS/PAM-D and use Ariane only

2) drastically change the PAM-D deployment sequence

3) change spacecraft hardware to increase the authority of the AND and/or increase the time constant.

The most promising option was to try, by some means, to increase the spacecraft's nutation time constant.

One way of doing this is to introduce baffles within the tank to inhibit the bulk motion of the contained fluid. But since the fluid motion characteristics were unknown, it was not clear what the baffle design should be. It was, therefore, decided to experiment with several baffles, designed to inhibit meridional and circumferential fluid motion.

11. DROP TESTS WITH BAFFLES

A second series of drop tests was initiated to investigate the effect of various baffle shapes on the nutation time constant. The baffles tested are shown in Fig. 10. Baffles 1 and 2 were designed to suppress meridional motion, while baffles 3 and 4 were intended to suppress circumferential motion. All the baffles were supported in the tank by being clamped between the tank shell halves. Baffle 1 is really an extreme form of Baffle 2 and not a viable design option. It was included to identify an effectiveness trend. Baffle 4 is a cruciform version of Baffle 3.

Testing indicated that, for both the pre- and post- PAM configurations, Baffles 1 and 2 were very much more effective than Baffles 3 and 4. The former increased the time constant by about an order of magnitude for the pre- PAM case and by about a factor of 4 for the post- PAM case. The latter had only a very small effect. See Figure 11. This was a very welcome result, as Baffle 2 is the easiest to implement in the tank hardware and involves only a very small increase (about 0.5 kg) in tank mass.

It was confirmed that Baffle 2 had the desired effect over the full range of parameter variations required to be explored.

The final series of tests was performed to optimise the design of Baffle 2. The design variables are the size of the central hole and position of the baffle in the tank. Both parameters were varied, and the results are shown in Fig. 12. These results show that optimum performance results when the diameter of the central hole is half the tank diameter, and when the baffle is mounted centrally in the tank shell. Such a design was, therefore, adopted for the spacecraft.

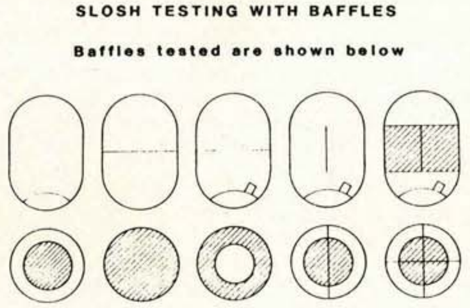

Fig. 10

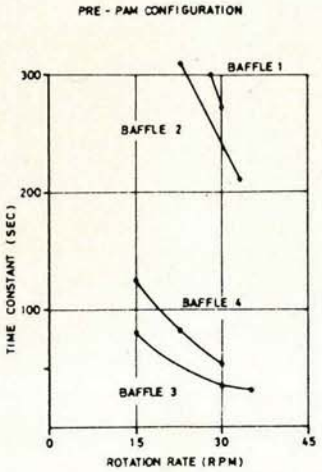

Fig. 11

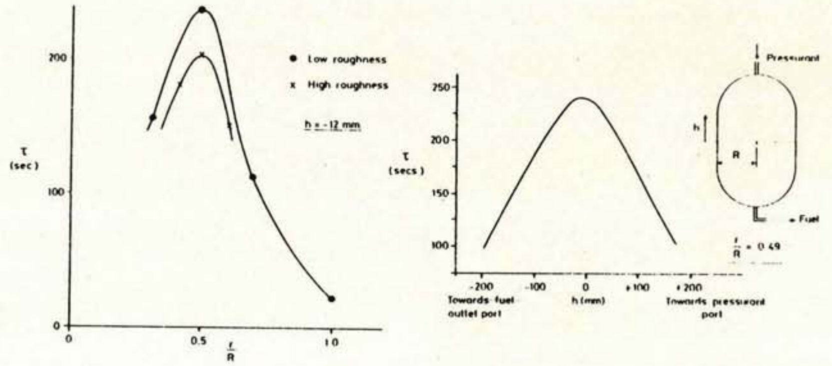

Fig. 12

12. CONCLUSIONS

The time constants resulting from the inclusion of baffles in the tanks are sufficiently large to ensure a safe and robust mission for the Eurostar spacecraft. During the test programme for the Eurostar spacecraft, the drop test method was used to:

a) uncover a problem;

b) investigate the problem;

c) evaluate various "fixes";

d) evaluate, comprehensively, the performance of the selected "fix" to yield reliable data for mission design.

It is the inherent cheapness and rapidity of the method that makes it suitable for use in an investigative mode. Various hypotheses can be explored quickly and economically.

Where a new spacecraft and/or propellant tank design is being considered, and slosh effects can be seen to require assessment, this should be done as early as possible to allow problem-solving to take place, If necessary, without disruption to the entire programme.

Another aspect of the testing is that although it can uncover a problem and help to explore it, it often cannot effectively diagnose it. Other "tools" must be brought to bear on the problem, which, together with test verification, can lead to a workable solution.

REFERENCES

1. J.V. Harrison et al., A Free-Fall Technique to Measure Nutation Divergence, and applications, Paper 83-372 in AAS/AIAA Astrodynamics Specialist Conference, Lake Placid, NY, August 1983.