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PREDICTING HIGH FREQUENCY VIBRATION TRANSMISSION ON SPACECRAFT

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1. INTRODUCTION

Future satellites will carry equipment which require low levels of vibration for their operation. Such vibration may be caused by the autonomous functions of the satellite maintaining its position on-station by use of thrusters and reaction wheels, and by other functions such as mechanical switches and antenna pointing mechanisms.

This paper describes a study to predict the level of high frequency vibration likely to occur on the ARTEMIS satellite due for launch later this decade. The mathematical model developed for the study is based on Statistical Energy Analysis. It was verified against the OLYMPUS satellite for which ground test vibration transmission data and on-station response data were available. The method was then used to predict the level of vibration that will be seen on ARTEMIS by scaling from the on-station OLYMPUS data.

2. THE SOURCE/TRANSMISSION/RECEIVER MODEL

Figure 1 shows a diagram of the major structural components of the ARTEMIS satellite and Figure 2 shows the SEA model produced for the study. The OLYMPUS satellite is similar in construction and was modelled with a similar SEA network.

Some of the main vibration sources of interest are thrusters mounted on the side panels of the satellite. When these are fired they produce a short duration force pulse. The thruster may be fired in a periodic manner which may affect the frequency content of the driving force. The resulting vibrational energy is transmitted around the satellite causing a response on the earth pointing panel which carries the sensitive equipment.

The basic SEA model shown in Figure 2 predicts the transmission of vibrational energy around the structure. The model needs to be extended to include a means of calculating the strength of the vibrational power input and the behaviour of the equipment attached to the earth pointing panel.

Little was known of the spectrum of the power input $P(\omega)$, and so this was estimated from the formula

$$P(\omega) = G_{FF}(\omega) \, . \, M(\omega)$$

where $G_{FF}(\omega)$ is the power spectrum of an idealised force pulse from the thruster and $M(\omega)$

is the mobility of the driving point. The mobility data was available from previous experimental work.

Because of the lightweight nature of satellite structures the equipment of interest constitutes a considerable mass loading on the earth pointing platform. It was assumed that the modal density of the platform (which affects the SEA power flow) was not changed by the presence of items of non-structural mass, and that the response of the equipment could be estimated using an impedance method recommended by ESA [1]. This is equivalent to assuming that so far as the equipment is concerned the satellite structure is acting as a force source. The acceleration response of the equipment, a_b was calculated from the formula

$$a_b^2 = a_p^2 \cdot \left| \frac{Z_p}{Z_p + Z_b} \right|^2$$

where a_p is the predicted response of the panel without equipment attached, and Z_p and Z_b are respectively the impedance of the panel and the equipment (which was assumed to be mass-like).

3. CHARACTERISTICS OF THE SEA MODEL

The SEA model was built using the GENSTEP computer program belonging to ESA. This program contains routines for calculating some of the SEA parameters such as the modal density and coupling loss factors.

The other parameter required in an SEA model is the dissipation loss factor of each subsystem. When a satellite is tested on earth vibrational energy is lost from the structure by at least three mechanisms; internal losses in the material of the satellite, damping due to radiation of sound, and energy losses due to air squeeze film damping between components and due to the presence of the reactive sound field created above each vibrating panel. When the satellite is on-station only the material damping is present.

Figure 2 shows the flow of energy around the SEA network at 100 Hz in the absence of air damping when a unit power input is applied to a side panel. The figure also shows the energy level of each subsystem and the power flow out due to internal dissipation.

As is to be expected for a weakly coupled system the source subsystem has by far the highest energy with nearly sixty times the energy level of the earth pointing platform. Of the power injected into side panel 92% is lost to internal dissipation within that subsystem and only 1.7% is transmitted to the earth pointing panel. Adding up the values of all internal losses gives unity as expected because of the energy balance equations on which SEA is based.

Two particular features of this application of SEA are worth further discussion. Firstly, SEA is normally applied to steady state problems in which the excitation is continuous and broadband. The second problem is that it is not usually considered desirable to apply SEA to point excitation problems,[2].

In the present case a short single transient of the type produced by a thruster firing is sufficiently broadband in the frequency domain. The transient nature of the problem may be avoided by considering a sufficiently long time window for any analysis.

For a single subsystem of loss factor η, which through an impulsive excitation is forced to vibrate with initial energy E_0 at time $t=0$ and frequency ω, the energy at time t is given by:

$$E = E_0 e^{-\eta\omega t}$$

The average energy over a time window of length T is given by

$$\bar{E} = \frac{1}{T}\int_0^T E(t)\,dt = \frac{1}{\eta\omega T}\left(1 - e^{-\eta\omega T}\right)$$

Hence if the time window is too short the $e^{-\eta\omega T}$ term gives an extra loss of energy and the damping appears to be higher than it should be.

The main problem with point excitation is that the number of modes of vibration excited by a point force are reduced thus decreasing the statistical confidence in the answer. Since in the current model the thrusters are attached to stiff parts of the structure and the modal overlap factors are high, the predictions from the analysis should be sufficiently accurate.

To test the model of vibration transmission the SEA predictions were compared with ground test data for the OLYMPUS satellite. For this purpose the model was extended from that shown in Figure 2 to include the effect of radiation damping. The material damping for each subsystem was estimated from previous test data. Figure 3 shows a comparison between the predicted and experimentally measured response of one item of equipment on the earth pointing panel due to a power input on one of the side panels. The result is normalised to give response per unit power input, so that this data acts as a test of only the transmission and receiver parts of the model. There is excellent agreement between predicted and measured vibration transmission up to 600 Hz. Above this frequency there is some evidence of poor measured data.

4. PREDICTED RESPONSE TO A THRUSTER FIRING

It would be desirable to be able to predict on-station vibration response due to any cause from knowledge only of the structure and the applied force spectrum. At the present time this is difficult because there is insufficient knowledge of the force spectra of the various vibration sources on board satellites.

In the case of a thruster however a certain amount is known of the shape of the force pulse that results when the thruster is fired for a short period. By taking this force pulse in the time domain, transforming to the frequency domain, and using the method described in section 2 it was possible to make a prediction of the expected response due to a thruster firing on board OLYMPUS.

Figure 4 shows a comparison between the predicted and measured vibration at an item of equipment on the earth pointing platform of OLYMPUS. The prediction has been performed for force pulses of two different durations to show the effect that this may have on the response, because the actual duration of the force pulse is not known when the satellite is acting autonomously.

Besides the problem that the spectrum of the force source is not accurately known errors may arise from two other causes. Firstly, the point mobility of the satellite at thruster location was not known precisely. Secondly, although the SEA model of vibration transmission has been tested against ground test data, it is necessary to reduce the structural damping of each subsystem due to the absence of the air damping. The radiation damping to air is known but the relative values of the damping due to the other mechanisms mentioned in section 2 is unknown.

In Figure 4 it is thought that differences between the measured and predicted spectra at low frequencies are due to errors in the estimated drive point mobility of the thruster mount. Differences at high frequencies are due to either the uncertainty in the pulse duration or to errors in the estimated structural damping.

5. METHOD OF SCALING FROM OLYMPUS TO ARTEMIS

The previous section shows the difficulties of making absolute predictions of vibration level from first principles when there is insufficient precise information.

Thus in order to predict the level of response that will be seen on ARTEMIS the best approach was to scale from the measured on-station response of OLYMPUS. The frequency dependant scaling factor was derived directly from the method outlined above to give the following relationship:

$$a_2^2(\omega) = \frac{M_2(\omega)\ T_2(\omega)}{M_1(\omega)\ T_1(\omega)}\ a_1^2(\omega)$$

where M_1 and M_2 are the point mobilities at the driving points on each satellite and T_1 and T_2 are the transfer functions from power input to acceleration response.

An advantage to this scaling formula is that, providing the damping on the two satellites is roughly the same, the exact value of the on-station damping loss factor is reduced in importance because the damping component included in the two SEA transmission coefficients will approximately cancel out.

6. CONCLUSIONS

Satellites may be represented by fairly simple SEA models and comparisons between the predicted vibration transmission and ground test data are in good agreement. Although estimating on-station response is complicated by lack of knowledge of the forcing spectrum and the structural damping, these problems may be avoided by using the model to scale vibration response from existing satellites.

7. ACKNOWLEDGEMENT

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8. REFERENCES

[1] ESA Structural Acoustics Design Manual, PSS-03-1201
[2] White & Walker, Noise and Vibration, Chapter 7

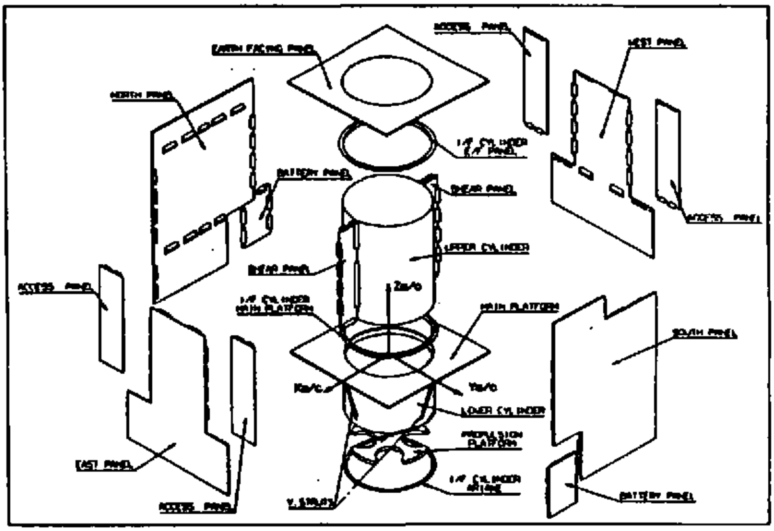

Figure 1 Main structural components of ARTEMIS

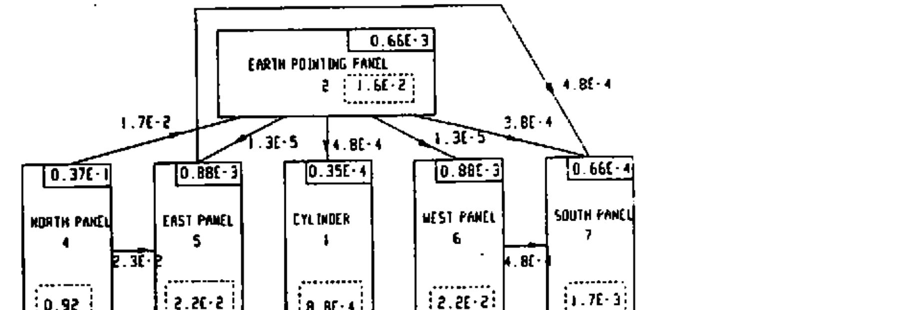

Figure 2 Power flow and energy levels around the SEA network for a unit power input in the 100Hz band to the North Panel

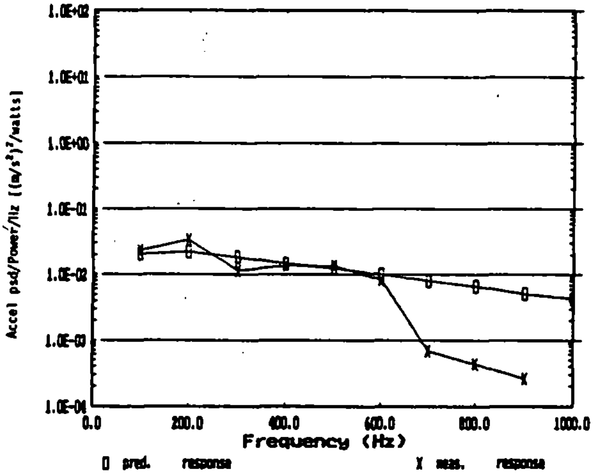

Figure 3 Comparison of predicted and measured response at an item of equipment on the OLYMPUS earth pointing panel for a unit power input to a side panel

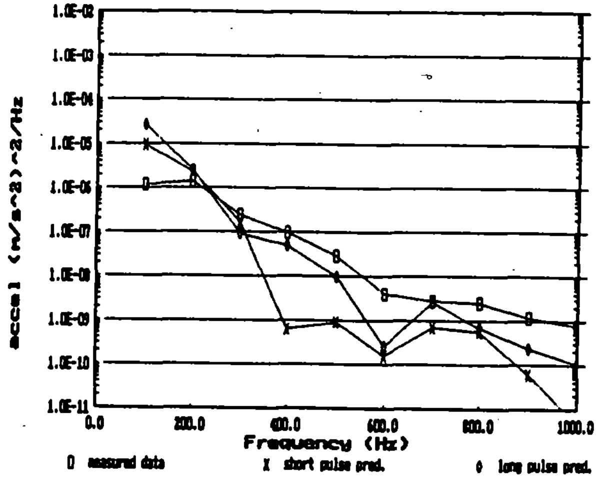

Figure 4 Comparison of measured and predicted response to an on-station thruster firing