SPACECRAFT VIBRATIONS DUE TO MECHANISMS; MEASUREMENTS FROM OLYMPUS ON-STATION

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ABSTRACT

When the Olympus satellite was launched on 12 July 1989, it carried a vibration monitoring experiment called PAX. The primary aim was to quantify the vibration environment and establish a database of the vibration characteristics of the on-board equipment. A secondary purpose was to enable the long term condition monitoring of the equipment.

Examples of on-station measurements are presented for several types of mechanism, such as wave-guide switches and antenna pointing mechanisms. These examples are always against a background environment contributed by other mechanisms and attitude control thrusters.

A brief description is given of the structural modelling which can be applied in order to estimate the signal characteristics at the mechanism location.

Payload and structure designers require to know the vibration levels to be applied to the structure by the mechanisms in order to control the payload's environment. Preliminary ideas on the development of standardised test rigs and procedures for measuring these characteristics are given. The necessity to design, or to select, a mechanism for a low level vibration characteristics is identified.

For the mechanism engineer, on-board vibration measurement offers the possibility of condition monitoring throughout the life of the equipment. This may be important in the case of anomalies or failures and particularly so if an incipient failure can be detected.

Keywords: Mechanisms, Vibrations, Olympus, Spacecraft, On-station.

1. INTRODUCTION

Various mechanisms exist on current spacecraft which can give rise to unwanted vibration on vibration-sensitive payloads, for example, optical payloads such as the inter-satellite link experiment SILEX on Artemis. Some of these mechanisms have been tested in laboratories on Earth whilst initial recordings of the space environment (Ref.1) have shown that previously unconsidered mechanisms should also be included in the list of significant vibration sources. A summary of the sources considered in this study are given below:

1. Thrusters
2. Reaction Wheels (R/W) and Momentum Wheels (M/W)
3. Wave-Guide Switches (WGS)
4. Solar Array Drive Mechanisms (SADMs)
5. Antenna Pointing Mechanisms (APMs).

In general, the information required for the above sources includes a detailed time history which shows the amplitude and duration, and the location of the sources. There are two alternative applications of the basic relationship which states that response is a function of both forcing and structural characteristics. Given a history of response measured on an in-orbit satellite, it may be possible to infer changes to, or degradation of, such sources from the vibrational response measured. On the other hand, if the source vibration output for a given source is known for both on-ground and on-station operation (normally similar outputs), and on-ground structural behaviour is known, then the structural behaviour in-orbit can be deduced.

In the study performed, the in-orbit responses arising from various sources were identified and ranked. Methods of automatic identification and classification were also considered. In addition, the in-orbit structural characteristics were sought to assist prediction of response on future spacecraft. However, as a result of the paucity of forcing data, primarily overall differences between on-ground and on-station response for the Olympus telecommunications satellite (Ref.2) have been investigated, both experimentally and theoretically and will be presented in the following sections. Ground test data has been used to update and improve the structural modelling which is then applied and compared with on-station data, but emphasis here is given to reporting the in-orbit responses.

Proc. 'Fifth European Space Mechanisms and Tribology Symposium', ESTEC, Noordwijk, The Netherlands, 28-30 October 1992 (ESA SP-334, April 1993)

Vibration is measured on the Olympus spacecraft using the PAX instrumentation (Ref.1) which is mounted on the telecommunications platform (Figure 1). Its specification is summarised in Table 1.

2. MEASURED ON-ORBIT VIBRATION

2.1 Individual Source Contributions

The total vibration at any moment is composed of contributions from sources which provide widely different characteristics. Their signals may be steady and continuous over long periods or be composed of short transients which may be repeated at a high rate over several seconds, they may be broadband or harmonic and cover a wide dynamic range. All these characteristics were observed in the PAX signals from Olympus which were processed for this study. The records mainly included periods of high mechanisms activity level acquired during the early on-station period.

In quiet periods, relatively random, broadband vibration was measured, in the range shown in Figure 2. The discrete components in these spectra have not been identified with sources running in the ground tests (reaction wheels, skewers, gyros), and may be due to those mechanisms running at different rotation speeds on-orbit.

Examples of harmonic signals are provided by the antennae pointing mechanisms (Figure 2), and are understood to arise from their stepper motors.

Transients typically arise from thruster firings (usually a few ms duration) and mechanisms such as wave-guide switches. Since most of the event time history period contains the structural ring-down, the signatures of transient events occurring at the start of the period are not very easily distinguishable. The maximum peak transient response observed on Olympus was the result of a wave-guide switch operation.

2.2 Microvibration Environment

Typical or maximum expected vibration levels arising from individually pre-identified events or epochs provide a basic definition of elements of the microvibration environment, but it is also useful to have descriptors of the distribution and frequency of these events and this requires a statistical approach. For descriptor development purposes, statistical processing was applied to some of the files available but because those files were of periods deliberately chosen for their high activity, the results cannot be considered as representative of normal periods in the life of Olympus.

The raw data files were processed to give the time histories of five measures of the vibration levels. An example is shown in Figure 3, which shows a four minute period of miscellaneous events. The first, second and fourth statistical moments of the PAX signal level (mean, standard deviation and kurtosis) are shown. Kurtosis is a measure of the impulsiveness of a signal; a harmonic signal has a value of 1.5, a Gaussian random signal has a value of 3, and spiky signals have higher values. Kurtosis values are therefore one helpful indicator or classifier of event type and thus of source type. Also measured were the levels of the raw data exceeded for ten percent and ninety percent of the time in contiguous blocks of data of about 1.3s (4,096 values at 3125/s rate).

A log of the kurtosis value yields an event count. If values below 2.5 are termed negative events and those above 4.0 are termed positive events and if the events are described as 'long' if the kurtosis value remains outside the 2.5 to 4.0 range for more than 4s, then Figure 3 contains 37 positive events (all short) and 17 negative events (2 being long). The possibility of multiple events within blocks was not investigated. The probability density of intervals between events was obtained, for all events in all files, the most commonly occurring interval being about 5s and the mean interval about 9s.

Probability density functions for the four measures of signal level (mean, standard deviation, L_{10} and L_{90}) were also derived for the assembly of data files. For the 'quiet' vibration periods, the most common and mean standard deviation is about 2.5 E-3 m/s^2 whilst the events show a very broad distribution, indicating a wide variety of values. Similar characteristics were determined for the maxima and minima and L_{10} and L_{90} within the data blocks.

In addition to the statistics of time histories of extended periods, the individual events were examined with a view to establishing automatic event identification and classification by sources. Few events could be unequivocally identified as being predominantly due to a specific source, but from those available and the analyses performed (including FFT and shock spectra and event envelopes giving the 10 dB duration period (time within 10 dB of peak value) and L_{10} and L_{90} values), some indications of useful descriptors were apparent. Typical curves for a wave-guide switch, thruster firing and SADM operation are shown in Figures 4, 5 and 6. Of particular interest is the development of a heterodyning technique described in (Ref.2).

3. GROUND MEASUREMENTS OF SPACECRAFT STRUCTURAL CHARACTERISTICS

3.1 Summary of Available Measurements

On-ground structural tests can identify the transmission path characteristics which will operate on the mechanism forcing characteristics and therefore they will assist in interpreting the in-orbit response signatures arising from the mechanisms as well as providing data for future prediction purposes. Allowance then needs to be made as far as possible for the modifications to structural response arising from in-orbit conditions, such as changes to damping mechanisms.

The experimental data processed from ground vibration testing of Olympus consisted of a set of tap (impulse) tests and continuous random input excitation tests at locations on the Olympus satellite, together with some self-excitation tests. When performing such tests, particular care must be taken to obtain good signal to noise ratios with the limited excitation levels permitted.

3.2 Character of the Satellite Response due to Mechanism Operation

This was examined for the operation of gyros and reaction wheels on the ground-based satellite. Measurements for individual mechanisms and for the background noise were intended to enable frequency components to be identified with particular sources. Some components in the response were also a function of the structural sensitivity at these frequencies. Generally there will exist narrow band components in such responses which can be identified as structural resonances and these were present in the spectra measured when various mechanisms including reaction wheels and gyros were running. The reduction in levels when the reaction wheels run down tends to indicate that components at 105 Hz, 120 Hz and 310-330 Hz were functions of the excitation in these cases. However, the very low vibration levels produced by such mechanisms (10^{-6}- 10^{-7} $(m/s^2)^2/Hz$ require great care in controlling background noise (including acoustic excitation) and recording levels in order to achieve good quality data from ground tests, and good signal to noise ratios were not achieved in the self-excitation tests.

As the input to the structure from the sources was not known, the transfer function could not be obtained from these tests.

4. STRUCTURAL MODELLING AND COMPARISON WITH MEASUREMENTS

4.1 Structural Modelling

The main mathematical model of Olympus is based on the Statistical Energy Analysis (SEA) method ((Ref.3) for ESA GENSTEP computer program). Although other techniques for modelling may be applicable, the modal-based techniques such as Finite Element Analysis (FEA) have much reduced confidence above the order of 20 modes, whereas the upper frequency limit of interest (up to the order of 1000 Hz) covers a much wider range. The SEA method is basically broadband and does not predict modal response. Since it predicts the vibrational energy in a structural sub-system, further analysis is required to estimate local response within the sub-system, such as at an equipment mounting location on a platform.

The layout of Olympus is shown in Figure 1 and the model developed for the predictions is shown in Figure 7. The on-station model without radiation damping comprises 7 subsystems and 10 coupling paths. Inclusion of the effect of acoustic radiation for on-ground modelling requires an extra subsystem and several extra coupling paths. This model is as simple as possible whilst including all the major transmission paths.

Some of the properties required for the model were deduced from the ground data. From a plot of accelerance (acceleration/force) or mobility (velocity/force), it was possible to obtain measures of damping associated with each mode of the structure as loss factor values in the range 0.03 to 0.11. From these values, a constant value of 0.04 was chosen for the model. Some of the measured damping values were thus two to three times higher than expected and the predicted values of response at the peaks will be correspondingly higher than measured by the same factor (ie, 6-8 dB difference on PSD levels).

4.2 Comparison with Ground Test Results

For comparison between the test data and the SEA predictions the test results were normalised to a unit power input. Above about 600 Hz the data was shown to be unreliable in many cases.

The behaviour of the model was first investigated by considering its sensitivity to the main parameters and then discrepancies from the measured response at PAX were compared with the likely effect of modelling uncertainties and the restricted scope of the model.

Point response at PAX was obtained by using the impedance formula in the ESTEC Structural Acoustics Design Manual (Ref.3). The prediction shows good general agreement with the measurements on ground, as shown in Figure 8 where the measured data is converted to wider bandwidth (100 Hz) to include sufficient modes as required for assessment by SEA.

The effects of the lack of radiation damping in space are shown in Figure 8 which shows that the energy transmitted to the Communication Module platform is reduced in air, with most effect at low frequencies.

4.3 Comparison with On-Station Data

A major difficulty in predicting the on-station vibration levels on Olympus is the lack of information on the characteristics of the various vibration sources. The dynamics of the wave-guide switches and the coupling of the impulse to the Olympus structure are not well defined. Reaction wheels and APMs are difficult to deal with because they are discrete frequency sources so that the response of the structure may be dominated by a few modes of vibration. As a result, SEA may be used to assess vibration due to this type of source only with reduced confidence in the prediction accuracy and a transfer function or FE modelling of the transmission path may be more suitable.

Only for thruster activity was it considered possible to predict the response measured by PAX because of the limited information available for other sources.

For thrusters, the character of the vibration will change with the duration of the impulse. For very short thruster burns, the spectrum depends only on the on-off impulse. For longer thruster burns, the spectrum will become dominated by the random components of the thruster. As the frequency content of the impulse is unknown, predictions are given for both types of duration.

The input spectra for the thrusters is calculated on the basis of a maximum impulse level of 22N and a duration of either 6 ms or 11 ms including a fall and rise time of 3 ms for both cases.

The structural models were modified to remove the effect of radiation damping to predict these results, but the changes in the coupling of the subsystems and the influences on the other sources of damping could not be quantified but these are most likely to have given secondary effects overall.

A method of transient SEA analysis described in (Ref.2) and a steady-state analysis were applied to the thruster pulse firings such as result in the measured response shown in Figure 5. These predictions are shown in Figure 9. The longer pulse prediction matches the measurement closely above 300 Hz, but both over-predict at low frequencies.

Given that the low frequency level of the force pulse is well defined from the information available since the low frequency level is insensitive to pulse shape, the most likely cause of the overestimate at low frequencies is that the mobility of the structure has been overestimated, possibly due to the thruster mounting being locally stiffened.

For a long continuous thruster burn, assumptions on the random variation in the thruster input produce a broadband force spectrum level of 7.9×10^{-4} N^2/Hz which is used in the steady state calculations for Figure 10. As for the very short burns, there is considerable overprediction at low frequencies, probably for the same reasons.

Direct comparison between the ground and on-station data is only available for the low level steady sources discussed in section 3.2. However it is not known for certain whether the same sources were operating in both cases.

5. VIBRATION TESTING PROCEDURES FOR MECHANISMS

Procedures for characterisation of vibration sources carry major practical implementation difficulties, as reported for on-ground application to structure-borne noise sources (Ref.4). The problems are based on the fact that vibrational power fed into the structure is determined by the degree of structural coupling between the source mountings and the structure and this in turn depends on the point and cross impedances of the mounting locations on the structure.

Simple test procedures are based on sources operating under conditions where either, (i) the whole equipment can be modelled as both a single forcing value in each of six degrees of freedom and a similar set of mounting impedance values; or (ii) each mounting location behaves as an uncorrelated source, each of which is described by such a set of forcing and impedance components. In these cases, each source or mounting operates as a 'monopole', the first type being a 'compact' source.

Whether the mountings are 'perceived' by the receiving structure as uncorrelated or not depends largely on the structure's characteristics. If the span between mounting positions is several wavelengths, or if there are high levels of isolation between the mountings and the structure, then the receiving structure will respond as if the inputs are poorly correlated. At the other extreme, less than a half wavelength separation generally causes the source to appear 'compact'. It is in the intermediate frequency region where phase between mounting location is required to be considered. The source may then be regarded as 'multipole', with mono-, di- and quadrupole components (Ref.6).

An assessment is needed to be made of which types of mechanism, given their usual mounting structures, are likely to behave as monopoles or higher order sources, and then test procedures need to be developed to suit.

A further consideration influencing the test configuration is whether external loading is necessary to cause typical vibration levels to be generated. For example, a wave-guide switch is a self-contained vibration source whilst vibration from a SADM is likely to be influenced both by its shaft inertia loading and by the inertial reaction loading applied to its mountings by the spacecraft, and the testing configuration would need to be more complex for the SADM. To avoid unnecessarily complex testing for some sources, it is expected that the first stage of a testing procedure will be assessment of the source to decide whether a simple or complex test configuration is necessary. The simplest configuration is likely to be low frequency suspension of a compact source which requires no external loading, with measurements required of vibration level and impedance at the mounting face. Direct measurement of vibration forces into a rigid fixture may be appropriate for a low mass source, but is limited in upper frequency range by practical limitations in achieving adequate stiffness. Multipole sources which require external reaction loading and those which produce transient vibration input will require the most complex test arrangement. These may require hard-mounting onto a structure providing typical impedance which will itself need to be characterised so that the source characteristics alone can be separated from the overall set-up.

Further knowledge is required of structural characteristics of spacecraft at typical source mounting locations before vibration power input estimates can be predicted with confidence.

6. CONDITION MONITORING OPPORTUNITIES

On-board vibration measurement provides the opportunity for aspects of condition monitoring of mechanisms, which may provide early warning of problems or provide useful information following a malfunction. The restrictions on telemetry bandwidth availability place an emphasis on on-board data reduction so that only a small amount of data is received on-ground until circumstances upgrade its priority. Further work is required on the classification of response signals and development of on-board data reduction and handling methods to achieve these aims. Some initial work on monitoring techniques based on PAX data are described in (Ref.5).

7. CONCLUSIONS & RECOMMENDATIONS

7.1 Vibration signals from Olympus on-orbit have produced much new data regarding the microvibration environment arising from spacecraft mechanisms. The measured responses are indicative of inputs to vibration-sensitive payloads and can also serve to monitor the mechanical performance and condition of the mechanisms.

7.2 Future work will require a combination of more detailed modelling of the local structure around sources with more detailed source data to permit accurate estimation of vibrational input power. This will enable not only better response predictions but could also be useful in interpreting the on-station response in order to identify and monitor changes in the mechanism.

7.3 To obtain source characteristics, a benchmark testing procedure for measurement of vibration power available from the source is required. This is a significant task, similar to the measurement procedure required for structure-borne noise output in on-earth situations.

7.4 Limited ground-based tests enabled some comparison with on-station data and improvement in the structural models. Limited knowledge of the sources produced difficulty in prediction of the on-board microvibration environment for comparison with the PAX data. By making assumptions on the force pulse shape from a short thruster burn an absolute prediction of one on-station event was made. The prediction required a combination of the assumed force pulse, the measured characteristics of the structure derived from the ground tests and predicted transfer function from the SEA model. A prediction of vibration due to a long thruster burn was also made. Where insufficient data prevented prediction of on-station events, methods for scaling response data from Olympus to other satellites can be applied Ref.3).

8. ACKNOWLEDGEMENTS

The authors acknowledge the contribution of the Signal Processing Group at ISVR in the PAX data analysis and assessment and the structural modelling work performed by M.G. Smith of ISVR Consultancy Services. ISVR thank ESA/ESTEC, Noordwijk, for their support of these investigations.

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Table 1: PAX Equipment Specifications (Ref.1)

Mass	2.37 kg
Power consumption	6.3 W (normal) 0.3 W (standby)
Current	125 mA (normal) 6.2 mA (standby)
Dimensions	200 mm long 134 mm wide 110 mm high
Operating temperatures	+80°C maximum −20°C minimum
Minimum eigenfrequency	1000 Hz
Frequency bandwidth	0.5 — 1000 Hz
Sensitivity	± 100 mg coarse mode ± 10 mg fine mode
Resolution	50 μg coarse mode 5 μg fine mode

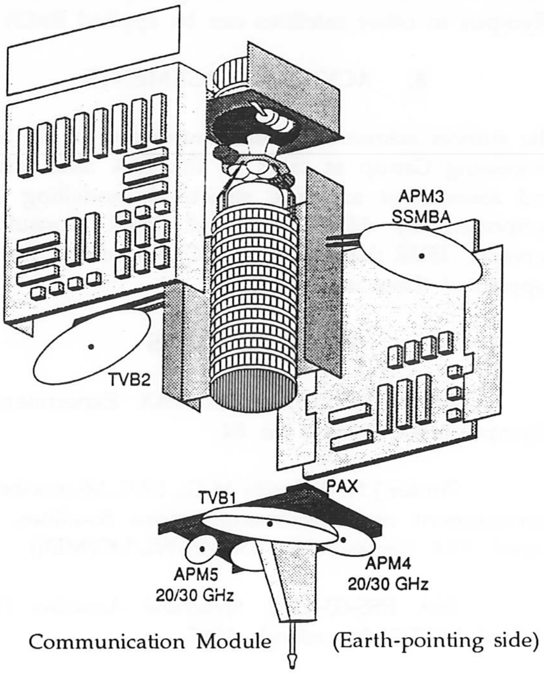


Figure 1: Sketch of Olympus Layout (Without Solar Arrays) Indicating Location of PAX Transducer

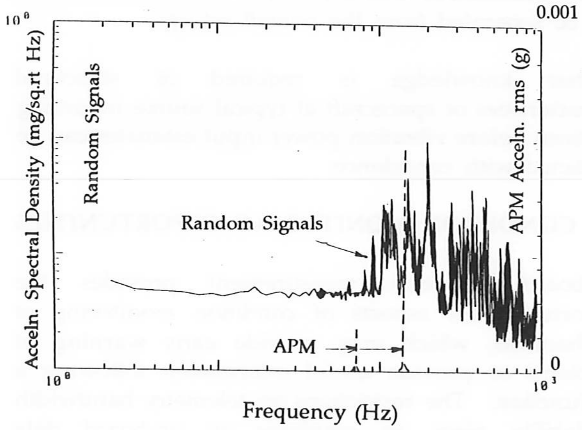


Figure 2: Spectra of Random and Harmonic Sources

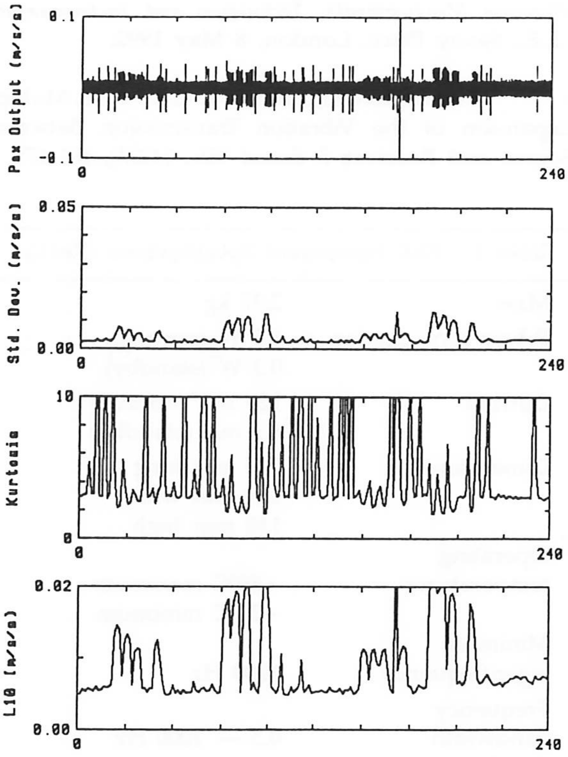
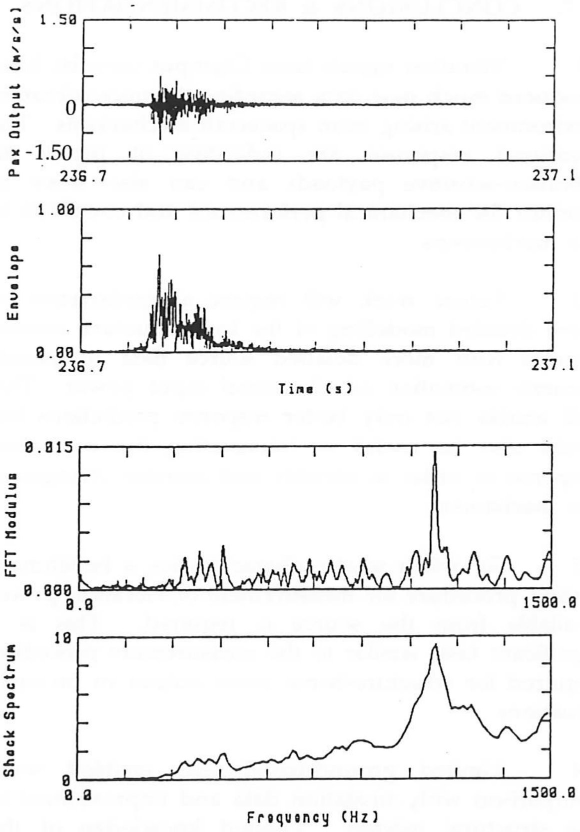


Figure 3: Time Record of Multi-Event File (On-station)



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Max:   .50583  Min:   -.61312  m/s/s
L10:   .15714  L90:    .00361
Envelope duration (10dB):    .0211s
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Figure 4: Response to a Wave Guide Switch Event

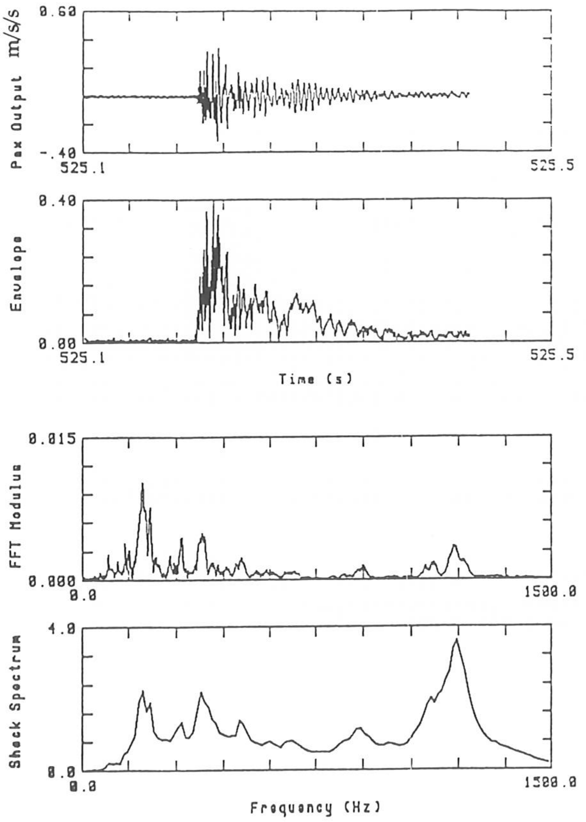

Figure 5: Response to Thruster Firing Pulse

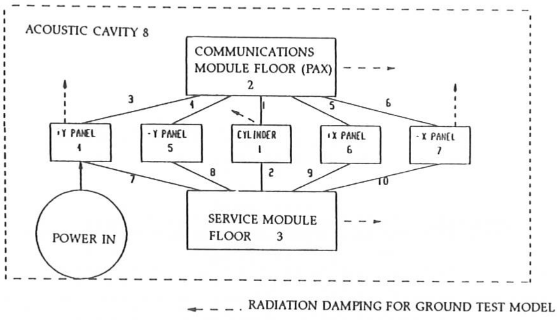

Figure 7: SEA Model of Olympus

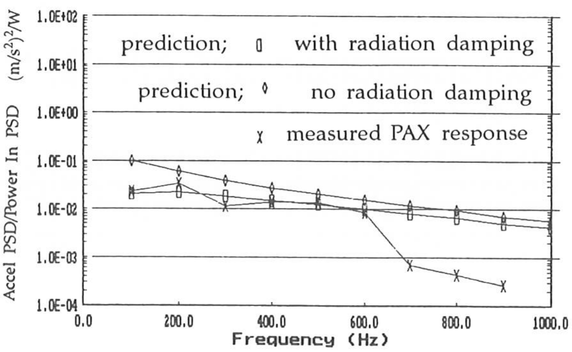

Figure 8: Measured Mean PAX Z-direction Response/ Power Input (for Three Input Locations) and SEA Predictions (Ground Tests)

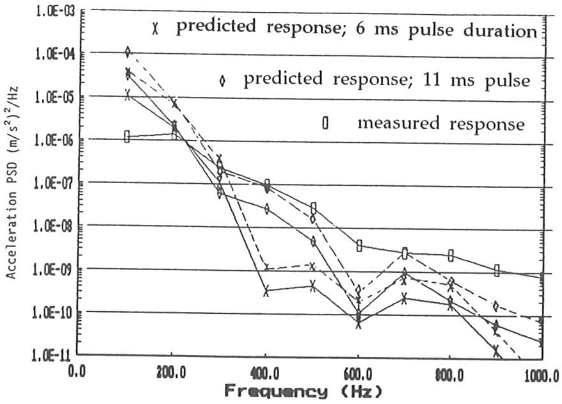

Figure 9: PAX Z-direction Response to Thruster Firing Pulses (On-station) solid curves; steady-state SEA method dashed curves; transient SEA method

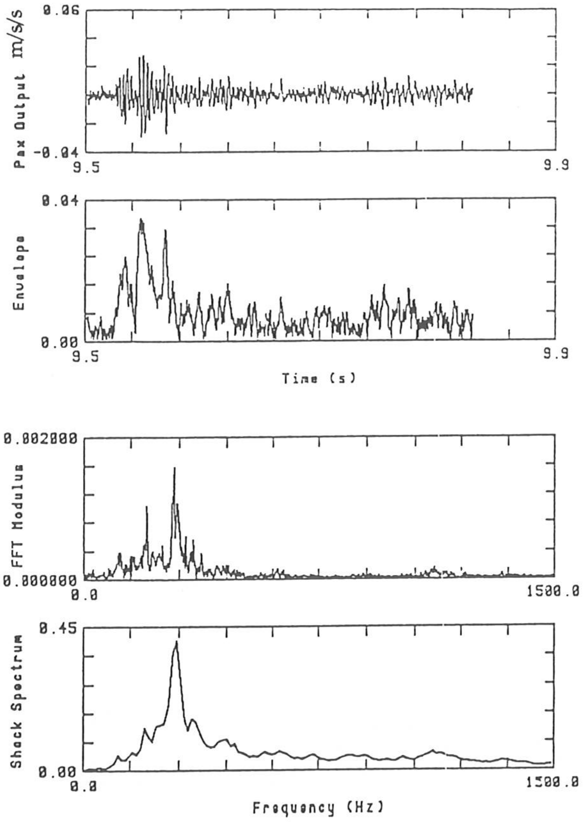

Figure 6: Response to a SADM Operation

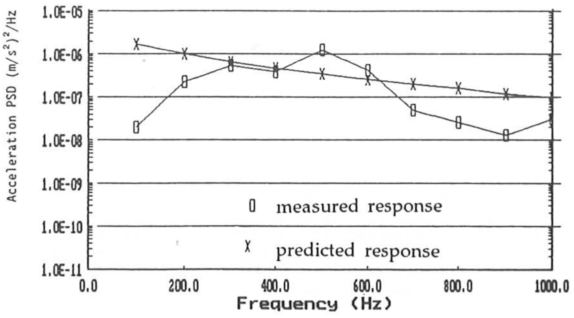

Figure 10: PAX Z-direction Response to Long Thruster Burn (several secs, random content)