VAPEPS MANAGEMENT CENTER

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BIOGRAPHY

Juan P. Fernández is the task manager of the VAPEPS Management Center at the Jet Propulsion Laboratory. For the past six years, Mr. Fernández has been involved with the development, utilization and maintenance of the VAPEPS program and has provided dynamics environments support to a number of]1'1, flight projects. He received his B.S. (1986) and M.S. (1988) in Aeronautics and Astronautics Engineering from the University of Illinois in Champaign-Urbana.

ABSTRACT

A VAPEPS (VibroAcoustic Payload Environment Prediction System) Management Center is established and being maintained at the Jet Propulsion Laboratory (JPL). VAPEPS is a computer program that utilizes statistical energy analysis (SEA) theory and SEA extrapolation methods to predict the vibroacoustic environments of complex systems. The program is commonly utilized to establish random vibration and acoustic test requirements for aerospace components exposed to launch environments. It can also be used in the payload or launch vehicle design process for control or mitigation of the launch or on-orbit vibration and acoustic environments, as well as to calculate acoustically induced stresses in structures such as solar panels and reflectors. This paper briefly summarizes the VAPEPS program capabilities and presents results of its application to the prediction of the vibroacoustic response of spacecraft solar panels.

KEYWORDS

SEA, VAPEPS, VMC, Vibroacoustics, Environment, Payload, Launch Vehicle, Solar Panel, Magellan, Mars Observer, TOPEX, Vibration, Acoustics

INTRODUCTION

Methods for developing aerospace vibroacoustic design and test requirements have improved significantly since the advent of computer programs based on statistical energy analysis. In the past, vibroacoustic analysis tools were more limited in their scope of application. For instance, conventional finite element analysis is generally limited to the low frequency range due to practical considerations such as complexity and computation costs. Also, extrapolation techniques are valid only if test or flight data from a similar structure exist. Current SEA based analysis tools provide a meaningful approach for understanding and estimating the mid to high frequency vibration of structures. The VAPEPS program has been in the forefront of more consistent and reliable methods for the prediction of vibroacoustic environments.

The VAPEPS Management Center (VMC) at JPL, originally established by the National Aeronautics and Space Administration (NASA) and the U.S. Air Force Space Division (USAF/SD), is currently sponsored by the NASA Lewis Research Center (LeRC). The VMC maintains the VAPEPS computer program and a data base of flight and ground test vibroacoustic data. The VAPEPS prediction techniques can be used with or without a data base to predict the mid and high frequency structural response of payloads or other aerospace structures. The program can also be used to predict the noise reduction through shrouds or panels, or to calculate acoustically induced stresses in structures such as solar panels and reflectors. The VMC also provides program implementation, improvement, and applications support to the VAPEPS community.

Since its inception, the VMC has actively promoted the use of VAPEPS in the aerospace community. The VMC has conducted numerous highly successful workshops to train analysts in the use of VAPEPS. The VMC publishes a VAPEPS Newsletter to keep users informed of new program developments. The VMC also provides user support for the distribution, installation and utilization of the program. As a result of its efforts, VAPEPS has become the most widely used SEA program in the industry. VAPEPS is used by more than forty organizations including six NASA centers and several educational institutions. At JPL, VAPEPS is used extensively for SEA modeling of all major projects such as TOPEX/Poseidon, Galileo, Magellan, and Cassini.

VAPEPS OVERVIEW

The VAPEPS computer program was developed by Lockheed Missiles & Space Company and Goddard Space Flight Center under the auspices of the USAF/SD and NASA [1]. The VAPEPS program was initiated because of the need for an analytical tool that incorporates the state-of-the-art in theoretical, empirical and data base generated vibroacoustic predictions.

The VAPEPS program consists of an extensive library of routines that can be subdivided into three major categories: theoretical and empirical prediction routines, general computational and analysis routines, and data base creation, search and retrieval routines. Each subset is described here briefly. The program is documented in Reference 1.

Theoretical and Empirical Prediction Routines

The basis for the VAPEPS prediction methodology is SEA [2]. This technique is statistical in nature and assumes that the excitation is random. The process under analysis is also assumed to be steady state so that energy balance equations can be applied. The prediction schemes take structural, acoustic space and excitation parameters of a dynamical system and provide an energy balance from which the mean-squared value of response can be calculated in one-third octave frequency bands. The most important SEA parameters for response prediction arc modal density, damping and coupling loss factors.

The modeling approach is to divide the payload structure into simplified SEA elements consisting of flat plates, cylinders, cones, beams or trusses and acoustic spaces. The inputs to the program include physical dimensions, material properties and damping loss factors for each SEA element. Next, the connect ions, or energy transfer paths, between elements are specified and an excitation level is input. The VAPEPS program calculates, in one-third octave frequency bands, the spatial and time averaged response of each element in the model to the given dynamic environment.

VAPEPS can yield purely theoretical or empirical predictions, or a combination of both. There are two extrapolation routines in VAPEPS, namely, EXTRAP I and EXTRAP II. EXTRAP I uses both the theoretical and scaling methods, whereas EXTRAP II uses only the scaling methods traditionally used in the aerospace industry. Each extrapolation procedure takes structural/excitation data sets of a baseline system, corrects for parametric differences between the baseline system and the new system configuration, and then establishes one-third octave power spectral density response values or decibel levels for the new system. Both extrapolation routines require a dynamically similar configuration to be used as a baseline model. The VAPEPS prediction routines are useful in establishing random vibration and acoustic environments for developing design and test requirements for new payload components.

General Computational and Analysis Routines

This category encompasses a wide variety of general mathematical and statistical routines for data manipulation and presentation. Also included are a set of vibroacoustic routines for calculating Fast Fourier Transforms (FFTs), Shock Response Spectra (SRS), overall grins levels, and performing other types of data analysis. These general procedures can be used alone or with a data base to obtain averaged or maximum levels, standard deviations and other data analyses.

Two notable vibroacoustic analysis routines in VAPEPS are the STRESS and TBLP commands. The STRESS command calculates a theoretical spatial average mean-square stress for a flat plate, curved plate, or cylinder based on an input mean-square acceleration response. The acceleration response input is assumed to be known either empirically or from a VAPEPS SEA prediction. Stress prediction results provide an estimate of the magnitude of the in-plane stresses in a structure. The estimate can serve as a guide for determining whether a design problem might exist and whether a more detailed stress analysis is in order. The TBLP command provides the capability to perform statistical energy analysis of simple structures under turbulent boundary layer excitation. The unsteady pressure field in a turbulent boundary layer is modeled as a progressive wave in the TBLP code. 'I'he command calculates the power input from a progressive wave field into a flat plate or cylinder.

I)ata Base Crest ion, Search and Retrieval

The VAPEPS program gives the user the flexibility to create a local data base using VAPEPS or to import data from a data base external to the program. Data base creation commands allow for spectra] accelerometer and microphone data, payload structural parameters and general bookkeeping information to be added to a data base. Data maybe entered in almost any form, however, VAPEPS automatically converts it to standard one-third octave band frequencies. Search and retrieval routines permit interrogation of the data base information. Retrieval commands can then be used to recover any required information from the data base, once a specific event of interest has been identified.

PREDICTION EXAMPLE

The following example illustrates the application of the VAPEPS vibroacoustic capabilities to the prediction of the acoustically-induced random vibration of large solar panels. Solar panels are of particular interest since they are commonly used in modern spacecraft to power electrical systems. These large surface area lightweight structures are easily excited by sound and often experience high acceleration responses during spacecraft acoustic tests. To demonstrate the capabilities of VAPEPS, vibration prediction results for models of the Magellan, Mars Observer [MO] and TOPEX spacecraft solar panels are evaluated and compared to acoustic test data.

VAPEPS Analysis

SEA Theory

SEA basically results in a procedure for analyzing the flow, storage and dissipation of energy in a system. An SEA model is developed by dividing the system into elements (i.e. plates, acoustic spaces, etc.) with groups of similar modes. The. modes of the system represent the energy storage elements. Energy is input into the storage elements by an external acoustic or vibration source. That energy is then dissipated by mechanical damping in the system and transferred between storage elements. Element responses arc then calculated from an energy balance in the system, The principal SEA parameters involved in this storage, dissipation and transfer of energy are modal density, damping and coupling loss factors [2].

Since SEA assumes that energy is stored in the modes of a structure. The fewer modes available for energy storage, the higher the variance in the response magnitudes and the more conservative the prediction. Normally, at least three modes per one-third octave band of analysis are required to allow for predictions with an acceptable degree of certainty.

Damping also plays a major role in the response of dynamical systems. Similarly, SEA response predictions are sensitive to the value of damping assumed for a model. Unfortunately, damping is one of most difficult parameters to determine accurately.

Description of Panels

Solar panels lend themselves to SEA due to their simple geometry and large surface area. All three solar panels are of lightweight, honeycomb construction with very large surface areas. A simplified model of each spacecraft's solar panel was developed from drawings and data of material properties [3-5]. The structural dimensions of the panels for the three spacecraft are listed in Table 1.

Modeling Approach

An analyst needs to be aware of the assumptions implicit in using a SEA approach as implemented in VAPEPS. The following are two important assumptions. First, SEA assumes that the resonant response of a structure is to be modeled therefore its use below the fundamental frequency of the solar panels is inappropriate, Second, it is assumed that a plate to be modeled is located in an infinite baffle such that sound cannot wrap around the edges. According to theory, this results in more efficient acoustic excitation of the plate and consequently higher panel response accelerations at low frequencies, below the plate's critical frequency.

Also, the VAPEPS vibroacoustic prediction routine, SEMOD, is applicable only to homogeneous isotropic model elements. Therefore, a multilayered

Structural Parameters	Magellan DMModel	Mars Observer	TOPEX
Length (in.)	99.2	89.3	129.4
Width (in.)	98.2	72.0	75.8
Facesheet Thickness (in.)	0.015	0.01	0.012
Core Thickness (in.)	0.50	1.00	1.35
Facesheet Material	Aluminum	Kevlar	Aluminum
Core Material	Aluminum	Aluminum	Aluminum

Table 1. Structural Properties and Dimensions **for the Magellan, Mars Observer and TOPEX Spacecraft Solar Panels**

stiffened panel needs to be *converted* into a homogeneous flat plate with equivalent properties. Equivalent structural properties were calculated using the RUN=EQPL routine. The processor computes an equivalent Young's Modulus, mass density and thickness for multilayered, stiffened plates.

A uniform modeling approach was used for all three solar panels to reduce the number of factors affecting the predictions. Each panel model consists of two basic elements: an equivalent homogeneous plate, PLAT, and an external reverberant acoustic excitation space, EXTA. The model parameters for each spacecraft solar panel, listed in Table 2, were input into the theoretical prediction routine. Then, each plate was coupled to its acoustic space using Path 49. Finally, each panel model was analytically subjected to acoustic excitation levels corresponding to its spacecraft's protoflight test levels.

The following modeling assumptions were also made for each of the solar panels. A scale factor of one (scalefac=1) is used for all solar panel model predictions. This assumption implies that analytically the model is acoustically excited on one side and that it radiates from only one side. An analyst can elect to use a scale factor between one and two based on the particular configuration of the system being modeled. Also, a damping loss factor (dlf) value of .05, equal to twice the critical damping ratio, was used for all three models. The damping

Model Parameters	**Parameter** (Units)	**Magellan**	**Mars Observer**	**TOPEX**
Thickness	**H** (in.)	0,701	1.738	1.7
Mass Density	RHO (lbs s^2/in^4)	2.45E-05	7.88E-06	1.17E-05
Surface Mass Density	RHOS (lbs s^2/in^3)	1.7213-05	1.3713-05	2.00E-05
Young's Modulus	E (lbs/in^2)	6.18E+05	2.15E+05	2.87E+05
Longitudinal Wavespeed	CL (in/sec)	2.01E+05	1.65E+05	2.20E+05
Surface Area	AP (in^2)	9741	6426	9808
Typical Sub-dimension	ALX (in)	98.2	89.3	77.6
Typical Sub-dimension	ALY (in)	49,6	72.0	45.5
Damping Loss Factor	DLF	0.05	0.05	0.05
Non-Structural Mass	ASMS (lbs s^2/in)	0.0	0.0	0.0
Pivot Frequency	PivotFreq (Hz)	250	250	250

Table 2. **VAPEPS Model Parameters for the Magellan, Mars Observer and TOPEX Spacecraft Solar Panels**

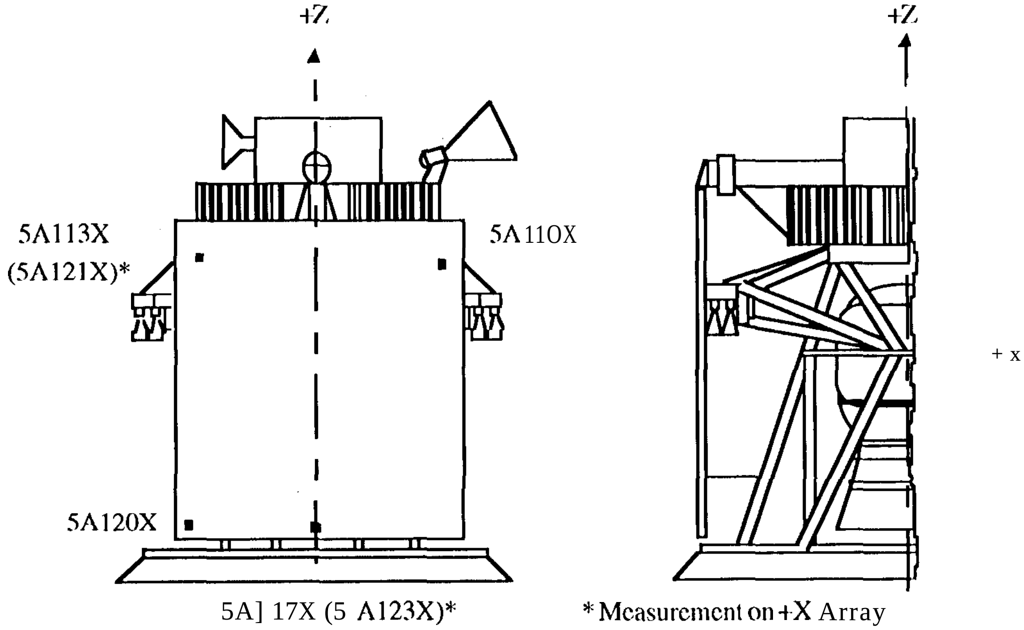

Figure 1. Magellan Spacecraft Solar Panels - Accelerometer Locations

function selected for the solar panel model is characterized as follows: a constant damping loss factor value of .05 below 250 Hz, and a value above 250117, that varies linearly with frequency by the following equation:

$$DLF = 0.05 * 250 \text{ Hz} / f \qquad f > 250 \text{ Hz}$$

(pivotfreq=250 Hz)

A consistent approach was also used to model the non- structural mass of the solar panels. Non structural mass is defined as component mass that is attached to the panel but does not act to stiffen it. There are two approaches to incorporating this type of mass into a model. The first and most common approach is to use the ASMS parameter. ASMS reduces the response of the panel model by a factor, M= Structural Mass / (ASMS + Structural Mass). The second approach involves incorporating the mass into the model by modifying the density parameter, RHO. The latter approach was used to model the mass of the solar cells for all three panels. It has the distinct advantage of reducing the response prediction at the low frequencies, where experience shows that VAPEPS tends to be conservative, much more than at the high frequencies. The ASMS approach reduces the prediction by a constant factor (M) across the frequency spectrum.

Predictions versus Acoustic Test Data

Magellan

The Magellan spacecraft system acoustic test was conducted at Martin Marrieta on March 1988 [6]. During this test, a dynamic mass model (DMM) of the Magellan solar panel was exposed to protoflight sound pressure levels (SPLs), 146.0 dB overall (OA). Figure 1 shows the panel instrumentation and configuration during the test. Data representative of the spatial average response of the panel were selected for comparison with the model response prediction. The data and the actual average sound pressure levels during the test are plotted in Figure 2.

Also, the VAPEPS average response prediction is compared to the spatial average response of the test data, Figure 3. The prediction agrees well with the data between 80-200 Hz and at frequencies above 800 Hz. However, it overpredicts the data by 3-5 dB between 200-800 Hz and is very conservative below 80 Hz. The significant overprediction below 80 Hz results from the panel having few modes at the low frequencies and from the panel being unbaffled, allowing the larger, low frequency acoustic waves to wrap around.

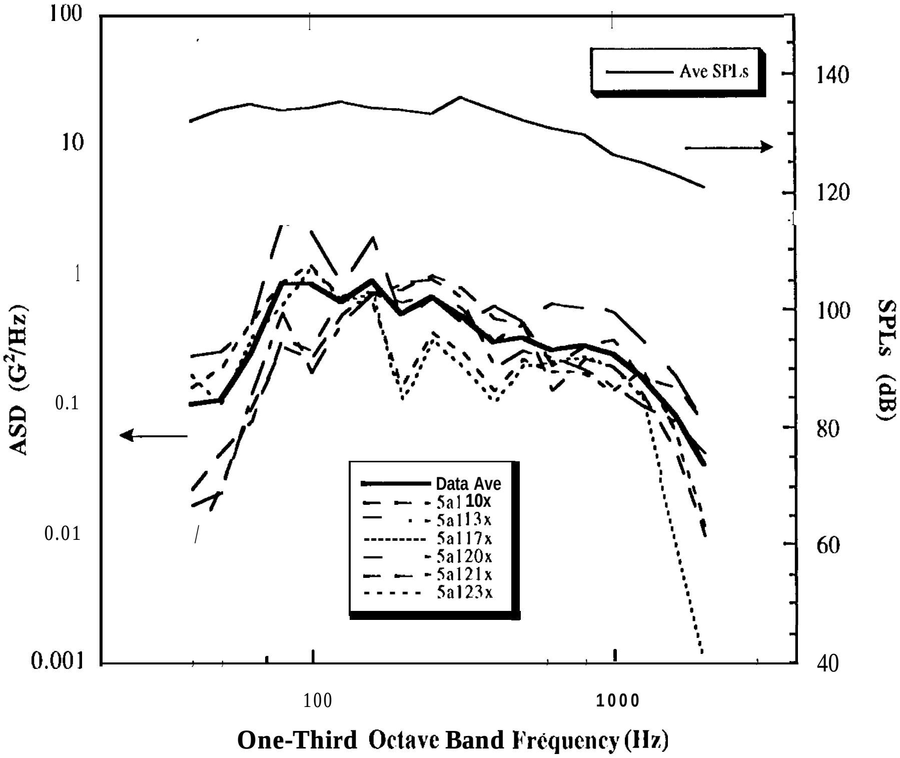

Figure 2. Magellan DMM Solar Panel Acoustic Test Data and Measured Average Sound Pressure Levels

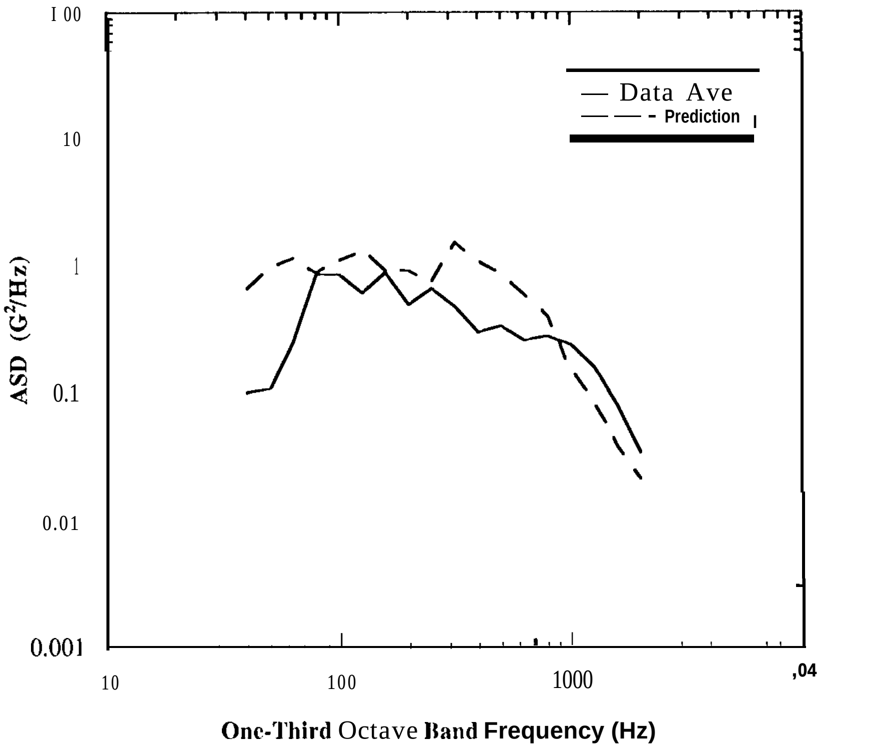

Figure 3. Magellan DMM Solar Panel Data Average Compared to VAPEPS Panel Model Prediction

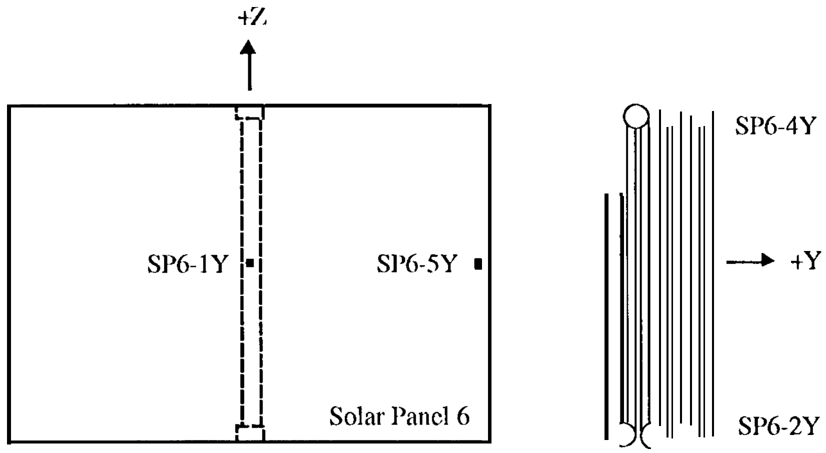

Figure 4. Mars Observer Spacecraft Solar Array - Accelerometer Locations

Mars Observer

The Mars Observer spacecraft system acoustic test was conducted at GE Astro Space on April 1992 [7]. The MO flight solar array was exposed to proto-flight S1'1,s, 145.8 dB OA, during this test. The solar array consists of six stacked solar panels hinged at the edges and held in the launch configuration by spring loaded attachments. Figure 4 shows the location of the accelercomers on panel 6, and the configuration of the panel array during the test. Response data from the outer panel and the actual average sound pressure levels during the test are plotted in Figure 5.

]'he VAPEPS average response prediction is compared to the spatial average response of the test

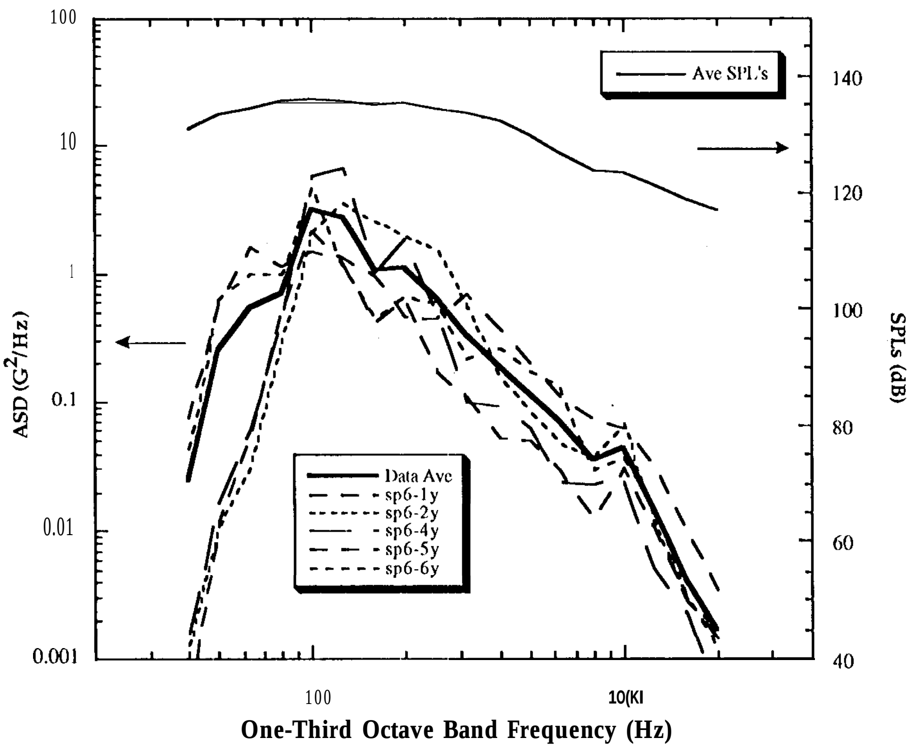

Figure 5. Mars Observer Solar Panel Acoustic Test Data and Measured Average Sound Pressure Levels

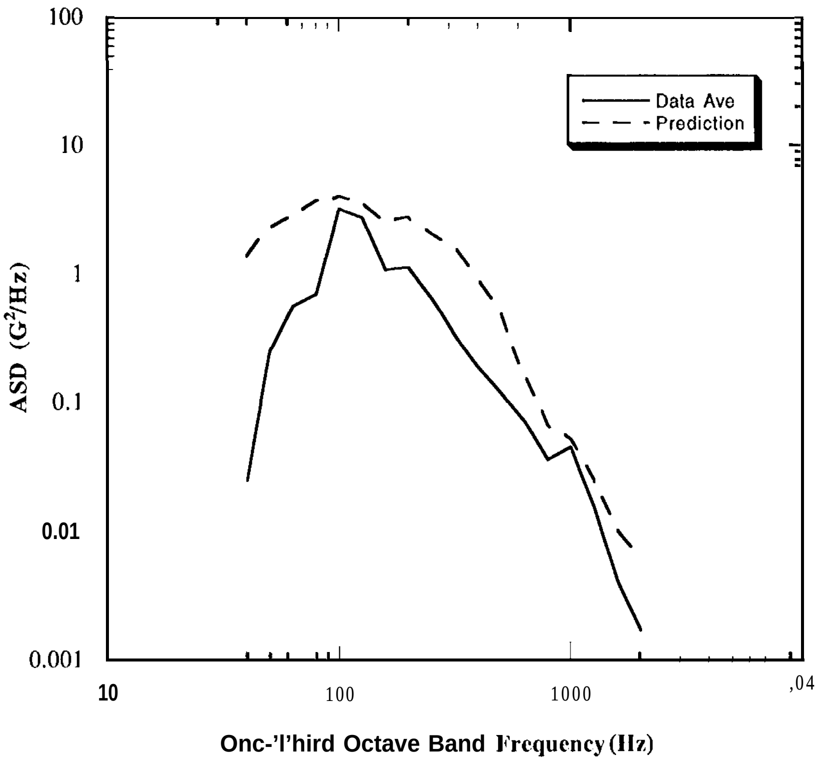

Figure 6. Mars Observer Solar **Panel** Data Average Compared to **VAPEPS Panel** Model Prediction

data in Figure 6. The prediction is conservative across the frequency spectrum. It is about 1-5 dB higher than the data above 100 Hz and much higher below 100 Hz.

TOPEX/Poseidon

The Topex/Poseidon solar array was tested to protoflight levels, 146.0 dB OA, during the satellite system acoustic test conducted at Goddard Space Flight Center on February 1992 [8]. The location of the accelerometers cm panel 4 of the solar array is shown in Figure 7. The solar array was tested in the launch configuration which consisted of the four hinged panels stacked and held together by four bolts. Response data from the outer panel and the actual average sound pressure levels during the test arc plotted **in Figure 8.**

In Figure 9, the VAPEPS average response prediction is compared to the spatial average response of the test data. The prediction is 2-4 dB higher than the data below 300 Hz, intersects the data at 400 Hz, and underpredicts the data above 500 Hz by 1-3 dB.

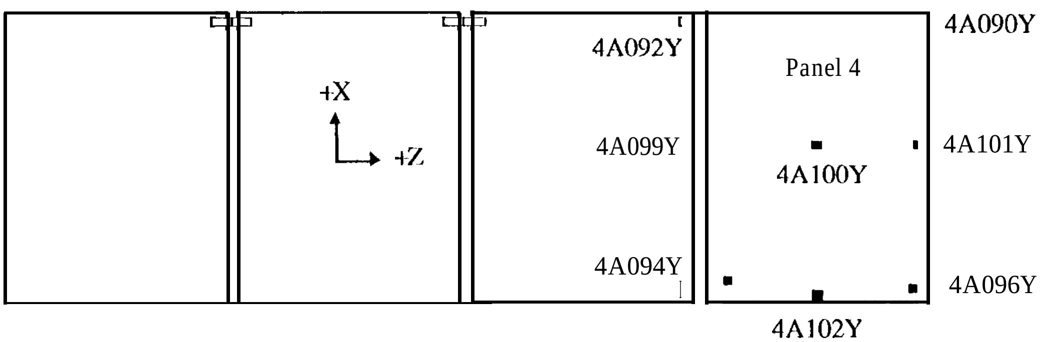

Figure 7. TOPEX/Poseidon Spacecraft Solar Array - Accelerometer Locations

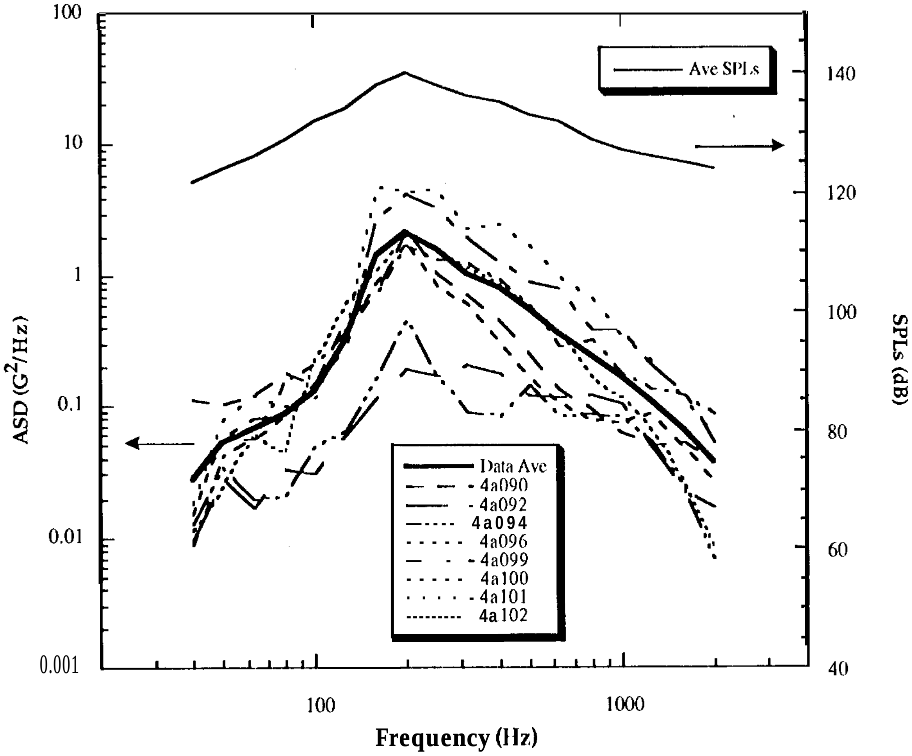

Figure 8. TOPEX Solar Panel Acoustic Test Data and Measured Average Sound Pressure Levels

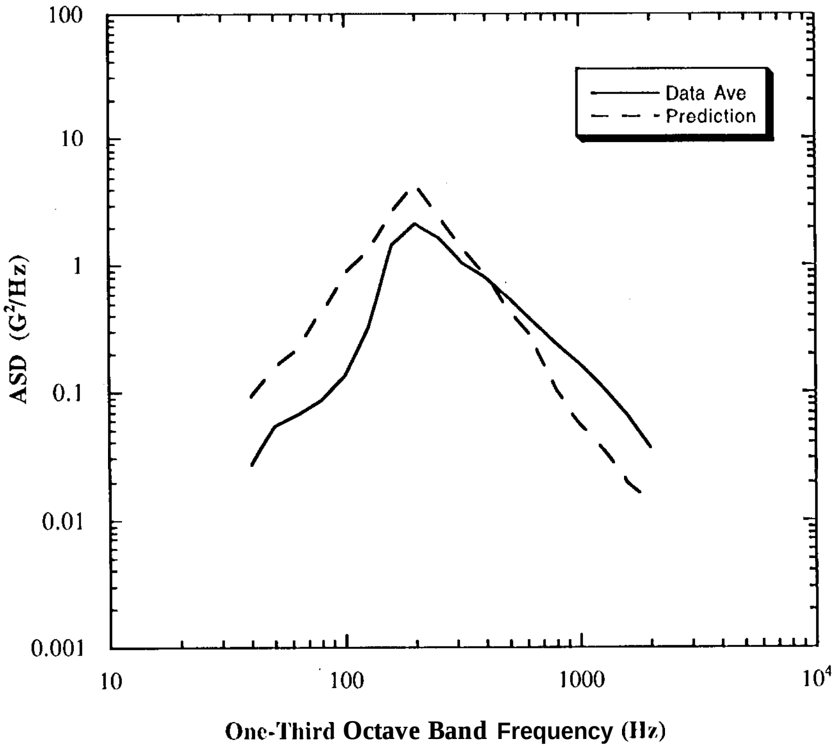

Figure 9. TOPEX Solar Panel Data Average Compared to VAPEPS Panel Model Prediction

Results

The MO, TOPEX and Magellan panel model predictions compared reasonably well with the acoustic data. Discrepancies in the comparison of the predictions to data are due in part to the modeling " assumptions made. For example, it is debatable. whether a scale factor of one for one-sided acoustic excitation was an appropriate assumption for the solar array models since one side of the outer panel is only partially shielded from the acoustic field. Also, the values of damping used in the models represent only an estimate of the true damping in the solar panels. Furthermore, the predictions represent the response of a homogeneous, isotropic plate simply supported in an infinite baffle; these conditions are seldom achieved in real structures.

Additionally, other non modeling factors can help explain the discrepancies between the model predictions and the acoustic data, For instance, each solar pane] was tested in a different launch configuration. The MO solar array consisted of six stacked panels, the TOPEX solar array consisted of four stacked panels and the Magellan solar array consisted of two panels, one on each side of the spacecraft. Each spacecraft test configuration imposes different boundary conditions on its respective solar panel array, which affects the characteristic response of the panels, particularly at low frequencies. Also, another factor to consider is whether the data used in the comparisons truly represents the spatial average for each solar panel.

Conclusions

It has been shown that SEA provides a meaningful approach for understanding and estimating the mid to high frequency multi modal vibration of large solar panels. The VAPEPS program gave useful estimates of the vibration response of the Magellan, Mars Observer and TOI'EX solar panels. Nevertheless, several points are made clear from the above presentation.

First, it is essential that the analyst have a good understanding of SEA principles to obtain rational predictions. l'here are many factors to be considered that can affect the accuracy of SEA predictions, It is therefore advisable to always perform an extrapolation prediction for a new model using available acoustic data from a dynamically similar structure. The data for the three spacecraft solar panels presented in this article can be used in that regard when modeling large panels. The best prediction is always that which can be validated with data.

ACKNOWLEDGEMENTS

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