COMPARISON OF MARINER ASSEMBLY-LEVEL
AND SPACECRAFT-LEVEL VIBRATION TESTS

Peter A. Franken and Terry D. Scharton
Bolt Beranek and Newman Inc.
Van Nuys, California
and
Thomas H. Mack
Jet Propulsion Laboratory
Pasadena, California

Results are presented of a study of vibration data obtained by the Jet Propulsion Laboratory in two series of tests of an electronic assembly from the Mariner C spacecraft. In one series of tests, the electronic assembly was mounted in a conventional vibration test fixture; in the other, the assembly was mounted in the spacecraft. The results of the study can be divided into two categories: those regarding the averaging of large collections of vibration data, and those concerning the differences between assembly-level and spacecraft-level vibration tests. Some recommendations are also given for future random vibration tests of aerospace structures.

INTRODUCTION

In the development of the Mariner C spacecraft, the Jet Propulsion Laboratory (JPL) obtained a large collection of vibration data in two series of vibration tests of an electronic assembly. In one series of tests, the assembly was mounted in the spacecraft (Fig. 1); in the other, the assembly was mounted in a test fixture (Fig. 2). In each series, vibration measurements at some 35 positions on the assembly were obtained at several test levels for both random and sinusoidal excitation, along three orthogonal excitation axes.

This paper presents the results of an engineering study of the vibration data obtained in the two series of tests. This study was conducted by Bolt Beranek and Newman Inc., but the data manipulations were performed primarily by JPL personnel utilizing JPL computational facilities. The primary objective of the data study was to compare the vibration environment of the electronic assembly in the spacecraft and fixture series of tests. Differences in both the assembly vibration characteristics and vibration levels between the two series of tests were investigated. A large part of the data study concerned the formulation of different averaging techniques involving averages over uniform spatial regions, similar components, measurement axes, excitation axes, etc.

DESCRIPTION OF ELECTRONIC ASSEMBLY, TEST CONFIGURATIONS, AND VIBRATION DATA

Electronic Assembly

The electronic assembly consists of 20 module boards containing electronic circuitry mounted to a flat chassis plate. The chassis plate (with accelerometers attached) is shown in Fig. 1, and the module boards are shown in Figs. 2 and 3. The chassis plate measures approximately 18 and 20 in. on the sides, and the module boards measure approximately 8 in. on a side.
Fig. 1 - Electronic assembly mounted in Mariner C structural test model spacecraft

Fig. 2 - Electronic assembly mounted in conventional test fixture
In the fixture test, the electronic assembly is mounted in a conventional vibration test fixture as shown in Fig. 2. The excitation levels in the fixture test are controlled by a single accelerometer oriented along each of the three excitation axes and attached to the fixture. Thus, the locations of the accelerometers used to control the excitation levels are quite different in the two types of tests.

Vibration Data

The vibration response data provided by JPL consisted of power spectral density (PSD) plots in the case of random excitation, and amplitude vs frequency plots in the case of sine-sweep excitation. The PSD data covered a frequency range from 100 to 2000 Hz and were plotted vs a logarithmic frequency scale, whereas the sine-sweep data covered a frequency range from 30 to 2000 Hz but were plotted vs a linear frequency scale. The PSD data were also available in digital form so that averaging and other manipulations could be performed automatically.

Data were available for 24 different runs which included low- and high-level random and low- and high-level sine-sweep excitation along three different axes, in both the spacecraft and fixture series of tests. Approximately 48 piezoelectric accelerometer instrumentation channels were recorded for each run. All response accelerometers, except those used for excitation control, were in the same position in the spacecraft and fixture tests.

SUMMARY OF RESULTS

Averaging Large Collections of Vibration Data

The results of the data study can be grouped into two categories. The first category of results concerns methods of averaging large amounts of vibration data to reduce the volume of data and obtain consistent significant trends. This data study resulted from the realization that some sort of averaging was necessary to reduce the volume of vibration data and to bring forth the most important features of the assembly vibration behavior. However, at the onset of the program, we did not know how much sophistication in the averaging techniques would be necessary to bring out the important vibration characteristics and to minimize the noise associated with fine-scale details.

The results of the study indicate that surprisingly little sophistication is necessary for effective averaging. For example, the gross
average spectra (averaged over all spatial regions, measurement axes, and excitation axes), shown in Fig. 4, illustrate many important features of the assembly vibration environment that could not be discerned readily from any single measurement. Our results also indicate that more complex averaging techniques (in which different spatial regions, measurement axes, and excitation axes were treated separately) reveal surprisingly little new information not contained in the gross average spectra of Fig. 4. Thus, it appears that a "law of diminishing returns" governs the results of the various averaging techniques employed. Of course, one might argue that the electronic assembly shown in Fig. 2 is a relatively simple structure compared to other aerospace structures (or in some cases, ensembles of structures) which are of interest in vibration data analysis programs. However, even in cases involving more complex structures, it seems reasonable that the first cut in the data analysis might well be a very gross average of all the data. These gross averages will often suggest examination of individual measurements or formulation of more detailed averages.

It is of additional interest to note that random excitation data were used to compute the average spectra shown in Fig. 4, since the sinusoidal data were not available in digital form. The study indicates that the results of random excitation tests, which are often more realistic than high-frequency sine-sweep tests, can be used efficiently to investigate the vibration characteristics of complex structures.

Differences Between Assembly-Level and Spacecraft-Level Vibration Tests

The second category of results is concerned with understanding the differences in the vibration behavior of the assembly between the fixture and spacecraft tests. Figure 4 illustrates some of the differences in the vibration environment in the two types of test, and Table 1 summarizes the results of a more detailed investigation of the differences.

Referring to Fig. 4, the large peak at approximately 1200 Hz in the average response spectrum for the fixture test is associated with resonance of the test fixture, and thus is not

![Graph showing comparison of average response spectra of electronic assembly in fixture and spacecraft random excitation tests.](image-url)

Fig. 4 - Comparison of average response spectra of electronic assembly in fixture and spacecraft random excitation tests

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TABLE 1
Comparison of Electronic Assembly Vibration Environments
in Fixture and Spacecraft Tests

<table>
<thead>
<tr>
<th>Source of Difference</th>
<th>Fixture Tests</th>
<th>Spacecraft Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Pronounced fixture resonance</td>
<td>No fixture resonance problems</td>
</tr>
<tr>
<td></td>
<td>Fixture provides coherent excitation</td>
<td>Spacecraft provides relatively incoherent excitation</td>
</tr>
<tr>
<td></td>
<td>Resonant response of module boards governs vibration</td>
<td>Above-resonance response of spacecraft modes governs vibration</td>
</tr>
<tr>
<td></td>
<td>Excitation axis is important except at high frequencies</td>
<td>Excitation axis is relatively unimportant</td>
</tr>
<tr>
<td></td>
<td>Module boards vibrate as rigid bodies at low frequencies, as cantilevers at intermediate frequencies and as a diffuse field at high frequencies</td>
<td>Module board vibration characteristics are similar to those in fixture tests</td>
</tr>
<tr>
<td></td>
<td>Average response is linear with small deviations from linear behavior</td>
<td>Average response is slightly nonlinear with larger deviations from linear behavior than in fixture tests</td>
</tr>
<tr>
<td>Levels</td>
<td>High levels at intermediate frequencies</td>
<td>High levels at low frequencies</td>
</tr>
<tr>
<td></td>
<td>Roll-off in response at frequencies above 700 Hz</td>
<td>Roll-off in response at frequencies above 100 Hz</td>
</tr>
<tr>
<td></td>
<td>Relatively large variations in chassis plate response but smaller variations in module board response</td>
<td>Roughly the same magnitude variations in chassis plate and module board response</td>
</tr>
<tr>
<td></td>
<td>Variations in response decrease with increasing frequency</td>
<td>Variations in response fairly uniform with frequency</td>
</tr>
</tbody>
</table>

characteristic of the assembly vibration. In the fixture test the average response spectrum is characterized by six response peaks in the frequency range from 350 to 700 Hz and then a roll-off in response of approximately 12 db/octave at higher frequencies. These six peaks are associated with the fundamental plate-mode resonances of the electronic modules (Fig. 3). The chassis plate (Fig. 1) to which these modules are attached acts to couple these module modes together and split the resonance frequencies apart. It is interesting to note that the 12 db/octave roll-off in the response at high frequencies corresponds to the theoretical result for the response of plate modes excited above resonance by motion of the supports [1].

In the spacecraft tests, the average response spectrum in Fig. 4 indicates that the overall spacecraft modes superimpose on the low-frequency end of the assembly vibration spectrum, and an attenuation associated with the vibration transmission through the spacecraft structure superimposes on the high-frequency portion of the spectrum. The results of more detailed averaging indicate that the direction of the excitation becomes insignificant in the spacecraft-level tests, particularly at the higher frequencies. The results also indicate that at low frequencies the variation in the assembly response is less in the spacecraft tests than in the fixture tests.

The study suggests some recommendations for more realistic fixture-mounted tests of individual assemblies in future spacecraft programs. Figure 4 indicates that future assembly-level tests should have less weight at high frequencies to be equivalent to spacecraft-level tests. The test results also suggest a means of avoiding the problems associated with fixture resonance in future assembly-level tests. In the
spacecraft tests the structure holding the as-
semlby has a complex modal pattern throughout
most of the frequency range of interest. This
suggests that a comparable "multimodal" mount-
ing be utilized in future assembly-level tests.
It is not difficult to visualize such a supporting
structure, and some model experiments along
these lines have been performed [2]. Additional
recommendations for future random vibration
tests are contained in the final section of this
paper.

DETAILED INVESTIGATION OF
ELECTRONIC ASSEMBLY
VIBRATION ENVIRONMENT

The vibration environment of the electronic
assembly can be explored in more detail by
treating different spatial regions, measurement
axes, and excitation axes individually in the re-
response averages. The spatial regions consid-
imated are the chassis plate, the module ears,
and the module boards. No distinction is made
among measurements on the five different
modules, so in every case the results represent
the average vibration environment of all the
modules.

Figure 5 illustrates the average response
spectra of the chassis plate for different excita-
tion and measurement axes in the fixture
random excitation tests. In each case the ex-
citation and measurement axes coincide. The
large peak at approximately 1200 Hz occurs
only for x-axis excitation. The fact that the
1200-Hz peak is characteristic of one excitation
axis in the fixture tests and is absent in the
spacecraft tests suggests strongly that this
peak is associated with a fixture resonance.

The five peaks between 350 and 700 Hz in
the y-axis response of Fig. 5 are very distinct.
These peaks are associated with resonance of
the fundamental plate-modes of the module
boards. (In experiments conducted at JPL, the
fundamental mode of a typical module board
was found to resonate at approximately 380 Hz.)
Since Fig. 5 indicates that excitation normal to
the chassis plate is a good exciter of the module
modes, the chassis plate must be strongly cou-
ped to the module modes in this frequency
range. The multiplicity of peaks between 350
and 700 Hz reflects splitting in the resonances
frequencies of the various boards introduced by
the chassis plate coupling. The x- and z-axis
responses in Fig. 5 indicate that the chassis

Fig. 5 - Average response spectra of chassis plate
in fixture random excitation tests
Figure 6 shows the average response spectra of the chassis plate for different excitation and measurement axes in the spacecraft random excitation tests. In each case the excitation and measurement axes coincide. Notice that the 1200-Hz peak in the fixture test response is absent in the spacecraft test response. At the lower frequencies, excitation perpendicular to the module boards (z-axis) and perpendicular to the chassis plate (y-axis) are better exciters than excitation in the plane of the module boards and chassis plate (x-axis).

The peak at approximately 100 Hz in the z-axis response must reflect a spacecraft resonance, since the chassis plate is stiff in its own plane. All the response curves in the spacecraft test exhibit several gross low-frequency resonances superimposed on a roll-off in response with increasing frequency. The response of the assembly in the spacecraft tests reflects primarily the above-resonance motion of low-frequency overall-spacecraft modes. The roll-off in the assembly response with increasing frequency can be explained either in terms of high-frequency isolation provided by the "soft" spacecraft mounting or in terms of an attenuation of vibrational energy at high frequencies as one moves away from the base of the spacecraft.

Notice from Fig. 6 that the direction of excitation becomes unimportant in determining the response at frequencies above approximately 300 Hz. This lack of dependence of the response on the excitation axis indicates that at frequencies above 300 Hz the excitation at the base of the spacecraft diffuses in direction by the time it reaches the electronic assembly. Thus, in random vibration tests of complex structures, excitation along a single axis is probably sufficient at high frequencies.

The absence in Fig. 6 of any pronounced response peaks in the 350- to 700-Hz frequency range may appear somewhat puzzling. One might expect the chassis-plate module-board modes, evident in the fixture test response of Fig. 5, to superimpose on the spacecraft response. However, the spacecraft test results indicate that these modes are not excited to any considerable extent in the spacecraft tests. One explanation for the fact that these modes are not excited lies in the possibility that the relatively flexible spacecraft mounting behaves like...
an incoherent excitation source in the frequency range of interest. Previous research [3] indicates that incoherent vibration fields, characteristic of aerospace structures at moderately high frequencies, are inefficient sources of excitation for single-degree-of-freedom systems, compared with coherent vibration sources. (Equation 17 of Ref. 3 shows that the energy transferred from the plate to the connected oscillator is proportional to the average modal energy of the plate. Thus, for a given vibration level on the plate, the energy transferred is inversely proportional to the number of plate modes which contribute to the vibration level of the plate.) The observation that the spacecraft vibration environment is diffuse above approximately 300 Hz lends credence to the incoherent source argument.

Average response spectra at different positions on the module boards show similar characteristics in the fixture and spacecraft random excitation tests. The responses at the three accelerometer positions of Fig. 3 are identical at low frequencies, indicating that the module boards move as rigid bodies. In the frequency range of the module board fundamental resonances, the response amplitude of the module boards decreases as one moves from the tip to the base. The module boards, therefore, behave as if they are cantilevered from the chassis plate. (The module board frames are bolted to the chassis plate and to the mounting racks at the module ears.) It is not difficult to envision a set of modes in which the module boards vibrate like cantilevers, and the chassis plate bending—vibration wavelength determines the relative phase between the motion of the individual modules. At the higher frequencies, the response spectra indicate that the vibration of the module boards is diffuse.

Figure 7 presents a comparison of excitation and response spectrum ratios in the fixture random excitation tests. The flat line at 4.5 db represents the ratio of high-level to low-level excitation spectra, and the response ratio curves represent the ratio of the responses in high-level tests to the responses in low-level tests. Thus, if the system were perfectly linear, the response ratio curves would coincide with the excitation ratio line. When the response ratio curves lie below the excitation ratio line, the results suggest common types of nonlinear behavior such as hardening spring and amplitude-dependent damping. When the response ratio curves lie above the excitation ratio line, the results suggest spurious or unexplained behavior. Figure 7 indicates that the average response spectra (averaged over measurement

![Fig. 7 - Comparison of excitation and response spectrum ratios in fixture random excitation tests](image-url)
from the chassis frame are bolted to the flat line at 4.5 dB level to low-level response ratio curves of the motion of the individual frequencies, the hat the vibration of.

Comparison of excitation ratios in the fixture and the chassis plate response measurements which show deviation from the average linear behavior. However, no explanation of these exceptional cases is available.

In the spacecraft test the average response spectra show a slight nonlinear behavior, predominantly in the low-frequency range. This nonlinear behavior in the spacecraft tests at low frequencies possibly reflects the fact that at low frequencies the specified acceleration levels result in relatively large motions in some selected regions of the complex spacecraft structure.

To provide an indication of the typical means and extremes encountered, Fig. 8 presents a comparison of the chassis plate response averages and 95th percentile levels between the fixture and spacecraft random excitation tests. The 95th percentile levels are based on a log-normal distribution. The data can couple into the assembly via the flexible spacecraft mounting, the variation in response is small. In the fixture test, where only the rigid body mode of the fixture is excited, the variation in response is large.

On the other hand, calculation of the means and extremes of the module board response indicates that the response variation in the fixture test is comparable to the scatter in the spacecraft test. Thus, the variation in response in the fixture tests decreases as one moves further into the electronic assembly - away from the fixture.
Figure 9 shows the ratio of the module board average response in the spacecraft test to the average response in the fixture test. The data represent an average over measurement positions and excitation axes. The measurement axis in every case is perpendicular to the module boards. Figure 9 indicates that the response of the module boards in the spacecraft tests exceeds the response in the fixture tests at low frequencies, and hence the fixture tests under-test the assembly. However, at high frequencies (above approximately 200 Hz) the response in the fixture tests exceeds the response in the spacecraft tests, and hence the fixture tests over-test the assembly. It is clear that some frequency shaping of the fixture-test excitation spectrum is necessary to achieve realistic assembly-level testing.

The results of this discussion of the differences in the electronic assembly vibration environments in the fixture and spacecraft tests are summarized in Table 1.

![Figure 9 - Ratio of module board average response in spacecraft tests to average response in fixture tests](image)

The curve in Fig. 9 can also be interpreted as the spectral density levels (in decibels) which must be added to the fixture-test excitation spectrum to achieve identical response of the module boards in the two types of test. The preceding statement is based on the assumption that the spacecraft and assembly behave linearly in the two tests. This assumption seems justified in the light of the small deviations from linearity observed.

It should be pointed out that even though the proposed shaping of the excitation spectrum would produce equivalent response on the module boards in the two tests, the response of the chassis plate might well be higher in the spacecraft test since the chassis plate is a less efficient exciter in the spacecraft tests, where the excitation is incoherent. This example bears out the point that it is usually not possible to simulate the response in every part of a complex structure.

The results of this discussion of the differences in the electronic assembly vibration environments in the fixture and spacecraft tests are summarized in Table 1.

**RECOMMENDATIONS FOR FUTURE TESTS**

The results of this study suggest the following recommendations for future high-frequency vibration tests of aerospace structures:

1. Develop and utilize multimodal test fixtures or mounting structures to avoid fixture resonance and sideband excitation.

2. Utilize instrumentation specifically designed for high-frequency testing.

3. Use fixture test results to predict spacecraft response.

4. Perform fixture tests under conditions that closely approximate those of the spacecraft.

5. Establish methods for determining the compatibility of fixture test results with spacecraft response.

4. Use experimental data from various space flight test programs to develop vibro-acoustic structure analysis and to provide realistic data for the development of vibration and acoustic analysis tools. The results from these tests are used to develop design tools for predicting the performance of structures under vibration and acoustic loads.

The results of these studies provide a basis for developing vibro-acoustic models of complex structures and for validating these models against experimental data. This approach allows for the incorporation of complex structure behavior into design tools, thereby improving the accuracy of predictions for vibration and acoustic performance.
REFERENCES

1. Private communication with R. H. Lyon


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INTROD