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

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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.

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## 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 6 in. on a side.

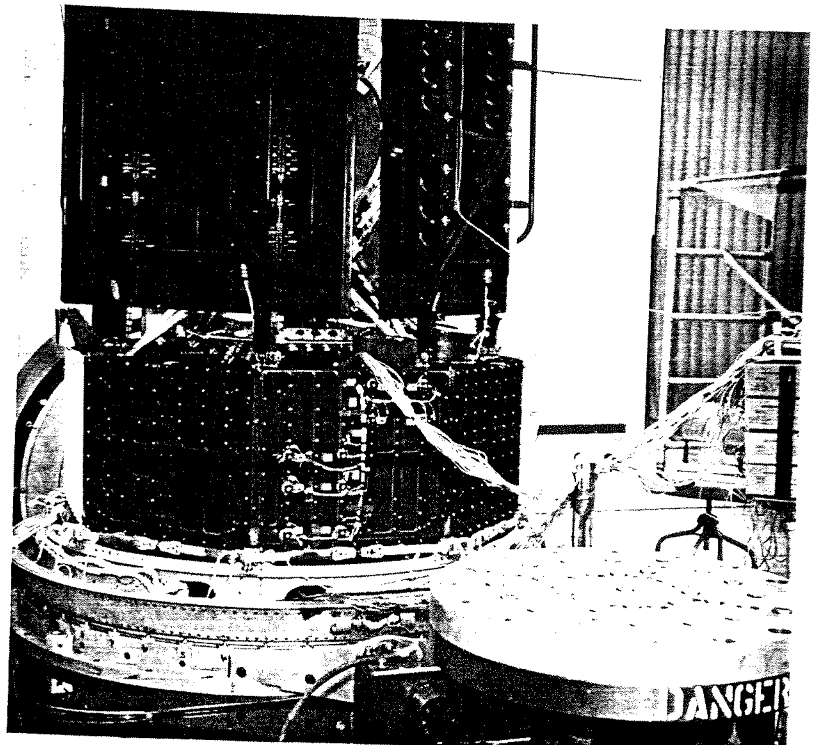


Fig. 1 - Electronic assembly mounted in Mariner C structural test model spacecraft

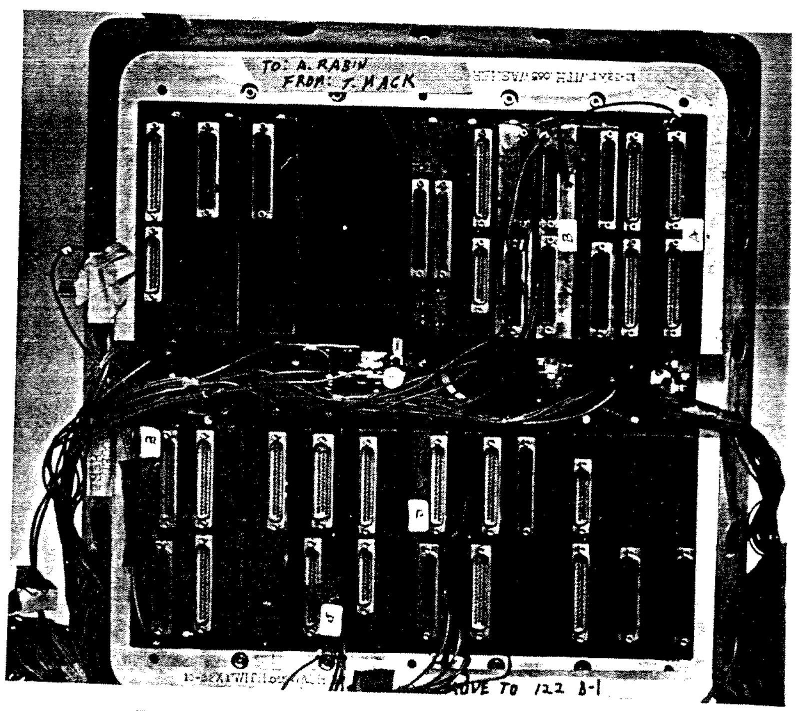


Fig. 2 - Electronic assembly mounted in conventional test fixture

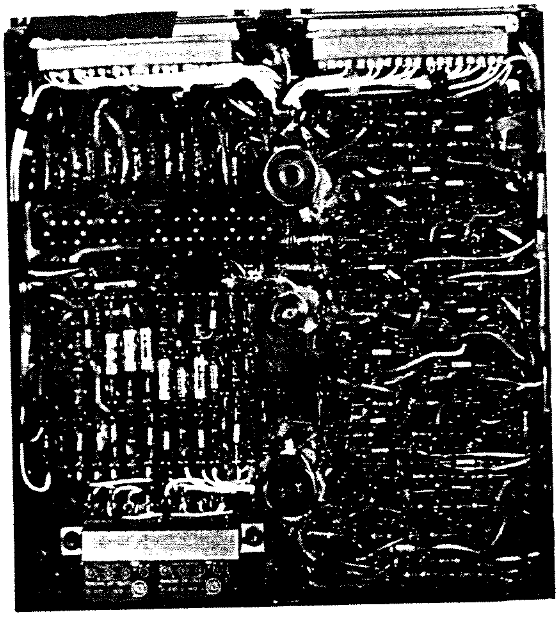

Fig. 3 - Module board from electronic assembly

Accelerometers for response measurement are located close to modules A, B, C, D, and E shown in Fig. 2. For each of these module boards, accelerometers are located in three different regions of the assembly: on the back side of the chassis plate (Fig. 1), on the module board ears where the boards are attached to mounting racks (Fig. 2), and on the face of the module boards (Fig. 3). It should be pointed out that all of these response accelerometers are positioned so as to measure specifically the vibration environment of the electronic components rather than the general vibration environment of the entire assembly. The accelerometers on the chassis plate and the module ears are triaxial, but those on the module boards measure only vibration perpendicular to the boards.

Test Configurations

In the spacecraft tests, the electronic assembly is mounted in the Mariner C structural test model spacecraft as shown in Fig. 1. The spacecraft, complete with adapter, is mounted on a ring-frame-type fixture attached to the mechanical shaker. In the spacecraft test, the excitation levels are controlled by the average response of six accelerometers oriented along each of the three excitation axes and positioned around the circumference of the ring-frame 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

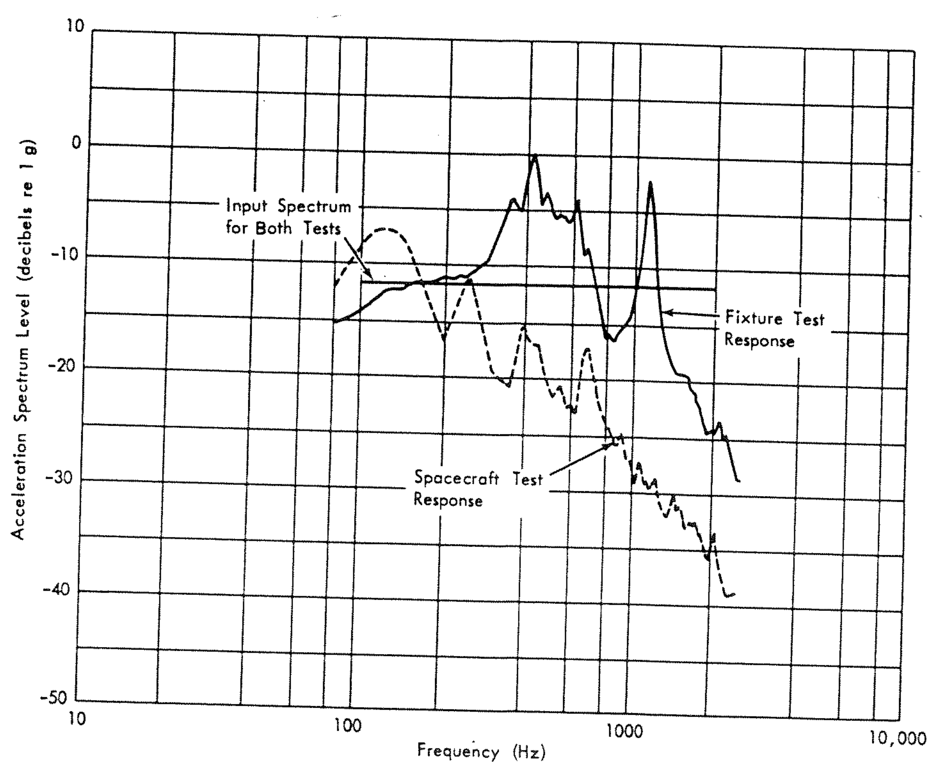


Fig. 4 - Comparison of average response spectra of electronic assembly in fixture and spacecraft random excitation tests

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

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

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 assembly has a complex modal pattern throughout most of the frequency range of interest. This suggests that a comparable "multimodal" mounting 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 response averages. The spatial regions considered 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 excitation and measurement axes in the fixture random excitation tests. In each case the excitation 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 coupled to the module modes in this frequency range. The multiplicity of peaks between 350 and 700 Hz reflects splitting in the resonance frequencies of the various boards introduced by the chassis plate coupling. The x- and z-axis responses in Fig. 5 indicate that the chassis

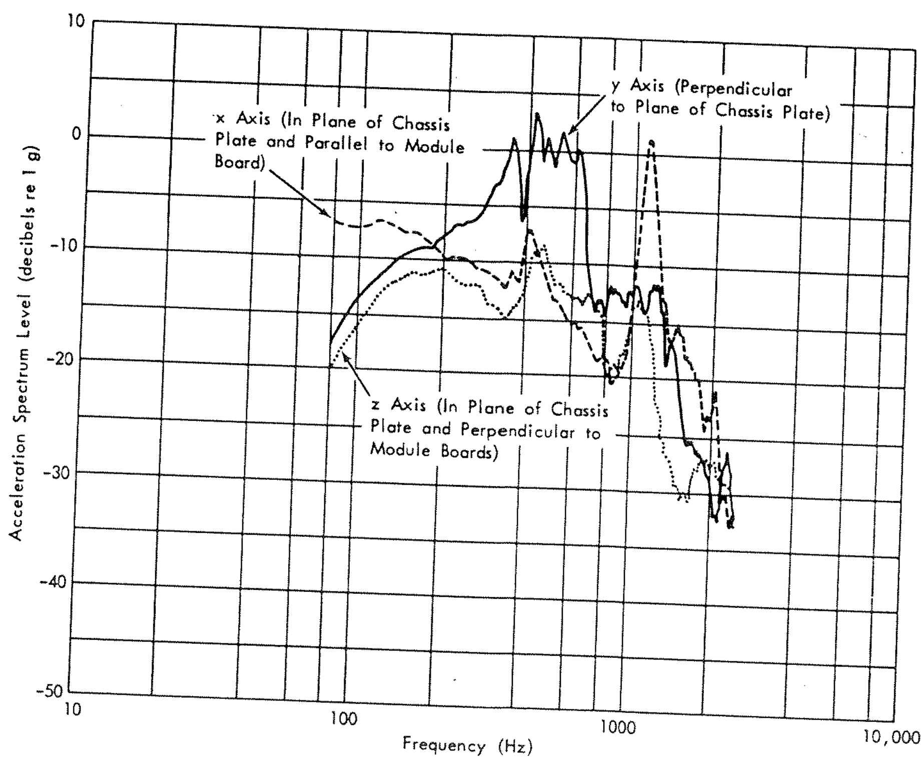


Fig. 5 - Average response spectra of chassis plate in fixture random excitation tests

plate remains stiff in its own plane over the entire frequency range of interest.

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

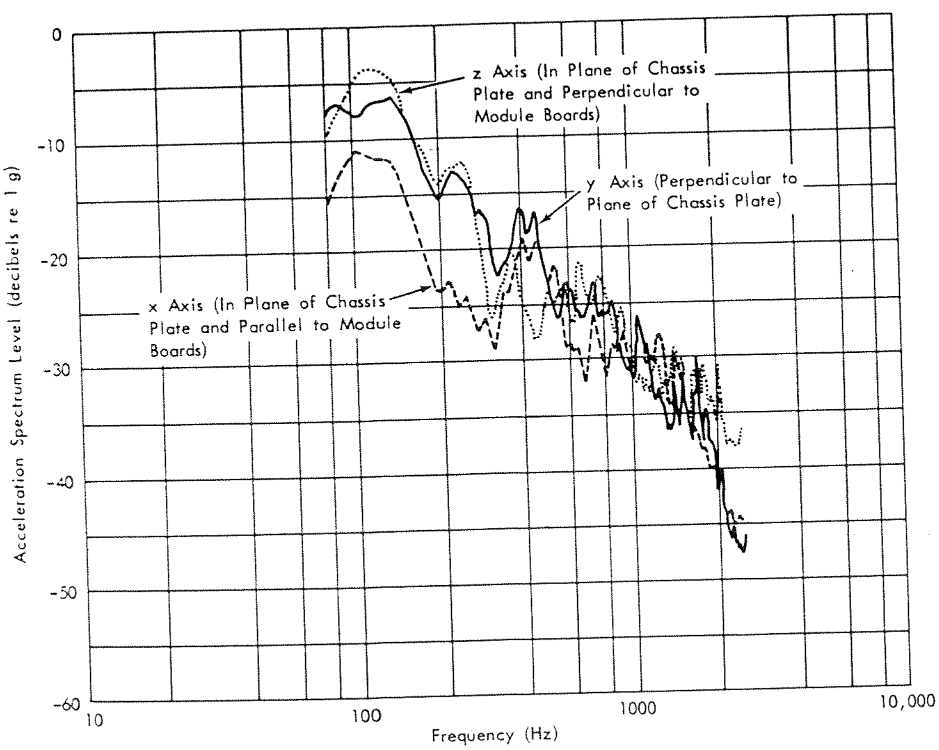


Fig. 6 - Average response spectra of chassis plate in spacecraft random excitation tests

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

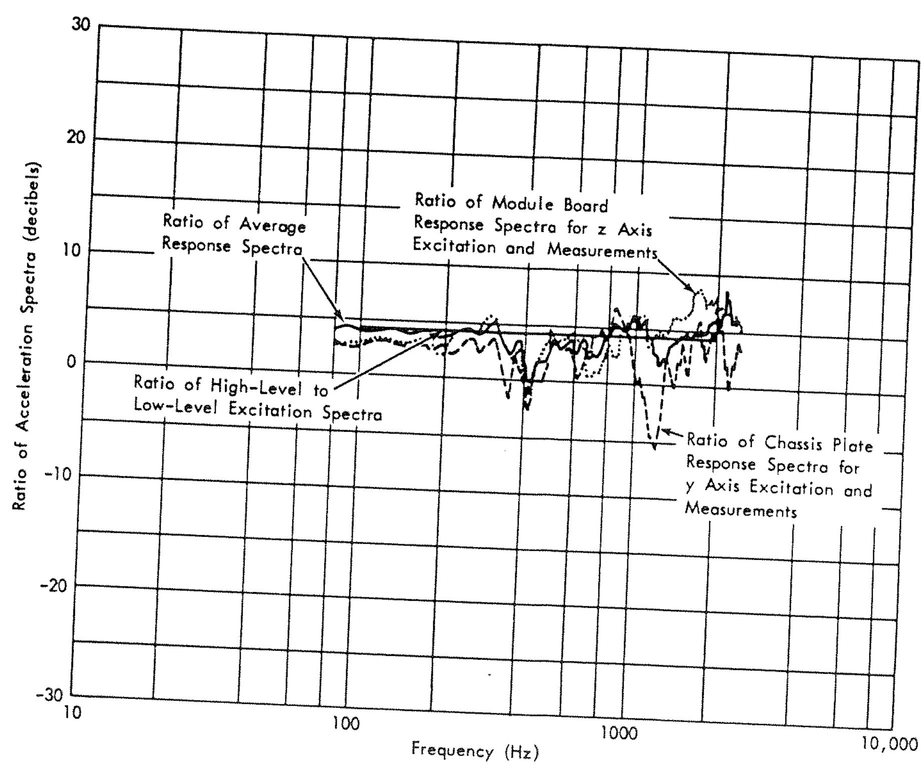


Fig. 7 - Comparison of excitation and response spectrum ratios in fixture random excitation tests

location, excitation axes, and measurement axes) of the assembly behave essentially linearly over the frequency range of interest. In addition to the ratio of average responses, we have also plotted in Fig. 7 response ratios for two particular 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

include different measurement locations, measurement axes, and excitation axes. Figure 8 indicates that the chassis plate response data show considerably less scatter in the spacecraft test than in the fixture test. This result is not unexpected, since previous research [4] has shown that the spatial variation in response is inversely proportional to the number of randomly excited modes which contribute to the response. The result is in the form of a central limit theorem which states that the variance of the sum will diminish inversely as the number of contributing terms. Thus, in the spacecraft test, where a large number of spacecraft modes

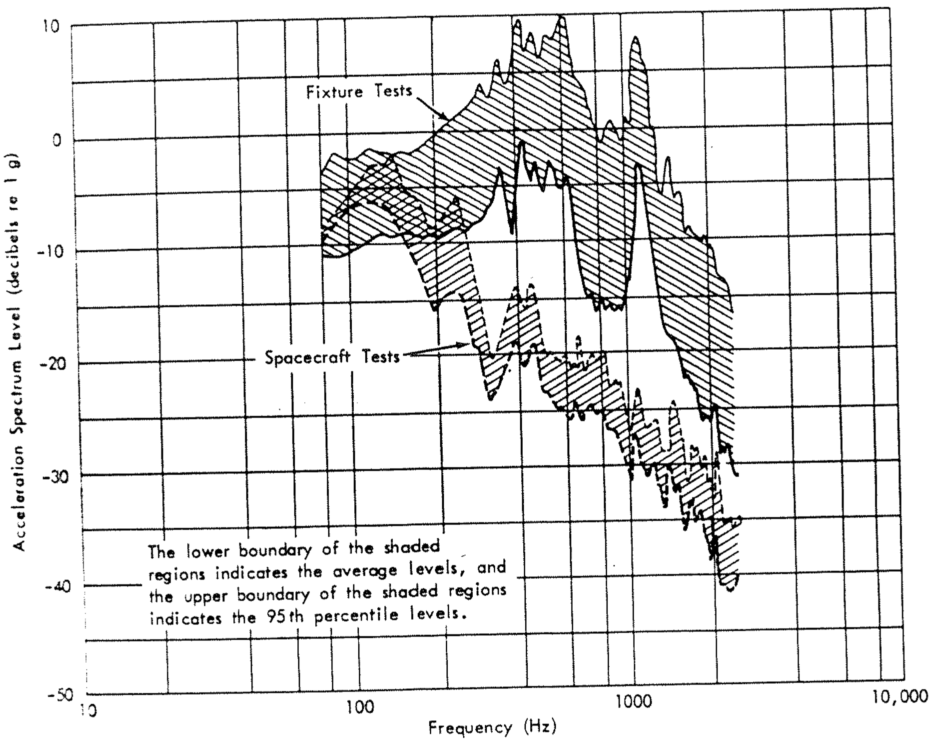


Fig. 8 - Comparison of chassis plate response averages and extremes in fixture and spacecraft random excitation tests

frequencies possibly reflects the fact that at low frequencies the specified acceleration levels result in relatively large motions in some local 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 undertest 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 overtest the assembly. It is clear that some frequency shaping of the fixture-test excitation spectrum is necessary to achieve realistic assembly-level testing.

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.

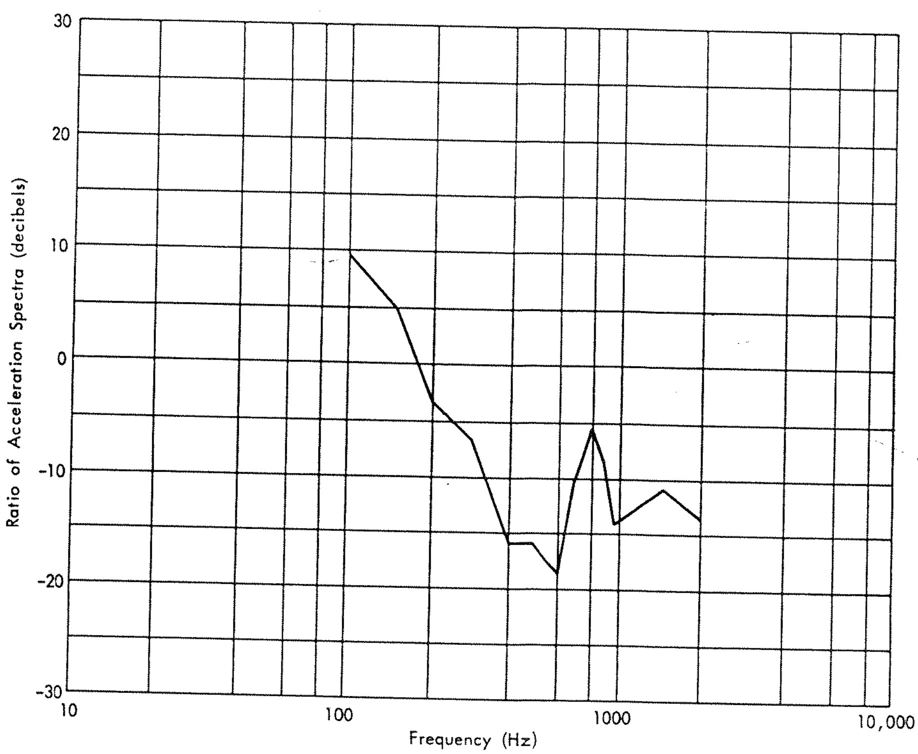


Fig. 9 - Ratio of module board average response in spacecraft tests to average response in fixture tests

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

## RECOMMENDATIONS FOR FUTURE TESTS

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

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

resonance problems and to provide more realistic excitation sources. In spite of considerable effort to design vibration test fixtures as rigidly as possible, the first bending resonance of conventional fixtures often occurs within the frequency range of interest (approximately 1200 Hz for the Mariner C electronic assembly fixture). As Fig. 4 illustrates, fixture resonance problems can easily result in extremely misleading vibration data. In addition, the coherent source of excitation provided by a rigid fixture is unrealistic and often results in severe overtesting.

The fact that resonance problems and coherent rigid body motion are not characteristic of typical aerospace structure suggests a means of alleviating these problems — design fixtures of light, flexible, multi-modal construction to simulate aerospace structures. We have investigated the use of multimodal fixtures briefly, and the results of our investigation look encouraging.

2. Shape the excitation spectrum in assembly-level tests to compensate for the structural filtering which occurs in spacecraft-level tests and under in-flight excitation conditions. Figure 9 indicates that mechanical vibration transmission through the spacecraft results in amplification at low frequencies and attenuation at high frequencies. These results indicate that assembly-level vibration tests on spacecraft like Mariner C should have increased weight at low frequencies. In contrast, results from other programs, involving the use of mechanical vibration tests to simulate acoustic excitation, indicate that the vibration tests should have increased weight at high frequencies to be equivalent to acoustic excitation. This apparent contradiction points out the necessity of understanding the relative importance of vibration and acoustic transmission paths in future aerospace structures. Some investigations of the vibration and acoustic transmission paths in the OGO and Surveyor spacecraft are in progress [5,6].

3. Exploit simplifications in testing procedures which are afforded by the diffuse property of high-frequency vibrations in complex structures. The results of this study indicate that in many cases the direction or exact location of the excitation source is relatively unimportant in determining the response. These results suggest that in the future it may not be necessary to perform random vibration tests along three different excitation axes — a test along only one axis may suffice. In addition, the possibility of utilizing a number of small mechanical shakers attached directly to the test item should be investigated.

4. Use experimental data from various spacecraft test programs to investigate broadband vibration transmission in complex structures. Although each spacecraft and vehicle is structurally different, we believe that the transmission of high-frequency vibration in complex structures depends largely on a few characteristic properties of the structure.

The results from a large number of programs, involving a wide range of structural configurations, should be analyzed to determine the dependence of vibration transmission on such structural properties as length of transmission path, mass of typical elements, average modal density, and internal damping. The results of such a data analysis program should include both average and extreme values of transfer functions as a function of the most significant structural characteristics. The results would provide guidelines and checkpoints for theoretical work as well as empirical prediction techniques for immediate applicability.

5. Conduct test programs and data-study programs concurrently. The advantages afforded by combining experimental and theoretical efforts in an integrated fashion are well known. Unfortunately, in the case of large programs involving many people and a large amount of equipment, it is not always possible to realize these advantages fully. However, we recommend that preliminary data be analyzed early in test programs to suggest additional and more meaningful tests. For example, one might average together all the preliminary data for a given type of test to obtain a crude picture of the vibration behavior such as that in Fig. 4.

6. De-emphasize high-frequency sine-sweep tests. It is well known that random qualification tests offer several advantages over sine-sweep tests — for example, random tests are less time consuming and usually more realistic. The results of this study indicate that random excitation can also be used in diagnostic tests to uncover the important vibration characteristics of complex structures at high frequencies. Of course, random tests do not provide detailed information available from sine-sweep and relative phase data, but at frequencies much above 200 Hz it is difficult (and usually unnecessary) to determine the exact resonance frequencies and mode shapes of complex structures. To make the most efficient use of test facilities, we recommend that sine-sweep tests of complex structures be avoided in the high-frequency range (above a few hundred Hertz).

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