Acoustic and Random Vibration Test Tailoring for Low-Cost Missions

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BIOGRAPHY

John C. Forgrave graduated from UCLA with a B.S. in Mechanical Engineering in 1977. He is a Registered Mechanical Engineer in the State of California. Mr. Forgrave has been involved in vibration and fatigue analysis throughout his career. At Garrett AiResearch he participated in the development of large gas centrifuges for the enrichment of uranium. As a private consultant he performed vibration and fatigue analysis on various types of machinery including wind turbines. At Marconi Dynamics he performed acoustic and random vibration analysis and testing on missile systems. At the Jet Propulsion Laboratory Mr. Forgrave performs sinusoidal, random and acoustic vibration analysis and testing to ensure the safe launch of interplanetary spacecraft.

Kin F. Man received his B.Sc. and D.Phil. degrees in physics from England. He has held research positions at the University of London and the United Kingdom Atomic Energy Authority's Culham Laboratory. In 1987, Dr. Man was awarded a NRC-NASA Research Associateship to study atomic collision processes in astrophysics and planetary atmospheres in the Earth and Space Sciences Division at the California Institute of Technology, Jet Propulsion Laboratory. He subsequently served as the Task Manager for Environmental Control in Microgravity Containerless Material Processing, as part of the Microgravity Containerless Processing Facility Project for the Space Station. Dr. Man is currently in the Reliability Technology Group at the Jet Propulsion Laboratory where he is managing and conducting research and development in various efforts to improve the reliability of spacecraft and their subsystems and components.

James M. Newell is a dynamicist in the Office of Reliability Engineering at the Jet Propulsion Laboratory, where he provides dynamic environment support for flight projects, conducts failure analyses using finite element techniques, and operates a vibration test facility. Mr. Newell also serves as a pressure vessel consultant to the JPL fluid and propulsion engineering group, and recently served as propellant tank Cognizant Engineer for the NSTAR ion propulsion system. Previously working in both engineering and management capacities at Fairchild Space Company, Hughes Aircraft, G.E. Marconi and TRW Pressure Systems, Mr. Newell is a registered California Professional Mechanical Engineer with over 16 years experience in the aerospace and related industries. He holds a Bachelor of Science degree in Mechanical Engineering from Old Dominion University, a Master of Science in Physics from Johns Hopkins University, and a Master of Business Administration from the University of Southern California.

ABSTRACT

Acoustic noise and random vibration tests are key constituents of an effective spacecraft environmental qualification program. Current test programs generally involve performing random vibration and possibly acoustic testing at the component level, followed by both acoustic and random vibration trials at the spacecraft level. Depending upon the surface area, mass and geometry of the test object, the acoustic environment may be more severe than random, or vice versa. Thus, for a low-cost mission, it may be cost-effective to eliminate one of the two tests at the component level, and to perform only the test that is most effective in screening for failure modes. This paper describes a method for optimizing acoustic and random vibration trials to reduce cost and schedule, by calculating a test article response in each environment and comparing the relative response magnitudes. Implementation of the method at the spacecraft level is also discussed.

KEYWORDS

Test Tailoring, Acoustic Vibration, Random Vibration, Low Cost Missions, Environmental Testing, Spacecraft Qualification, Dynamic Test optimization, Dynamic Response.

1.0 Introduction

The traditional approach for environmental testing of NASA's interplanetary spacecraft is to perform a full set of environmental qualification tests on engineering models of each subsystem, and to subsequently conduct acceptance tests on each flight unit. Once all subsystems are integrated into a fully assembled spacecraft, system-level environmental tests are then conducted.

This philosophy, while rigorous, is no longer justifiable in the cost-constrained, "Faster, Better and Cheaper" environment. There is increasing financial pressure on interplanetary spacecraft programs to reduce costs and, consequently, to optimize or minimize the number of tests in the environmental qualification program. One approach to such optimization is to calculate the relative effectiveness of each test, using an idealized analytical model. This paper describes the implementation of such an approach, focusing on the tradeoff between acoustic and random vibration at both the component and spacecraft levels.

2.0 Component Level Vibration Testing

Acoustic and random vibration tests are important constituents of the environmental test matrix in all flight projects. Current test programs generally involve performing both acoustic and random vibration tests at the spacecraft level, and usually one of the vibration tests at the component level.

In acoustic tests, acoustic noise is used to excite the component. The component is normally suspended in an acoustic chamber with a very soft mount, by placing it on a foam pad or suspending it from bungie cords. In some cases, electronic modules may be attached to larger metal plates to simulate actual mounting on the spacecraft structure, thereby creating a more realistic acoustic vibration profile. Loud speakers or horns are used to supply the acoustic energy, with microphones strategically placed in the chamber to control and record the sound level. Figure 1 shows a typical acoustic noise profile used to simulate the launch vehicle environment. The spectrum is divided into 1/3 octave bands, and the decibel (dB) sound pressure level is specified for each band. The input frequency range is typically from 30 to 10,000 Hz.

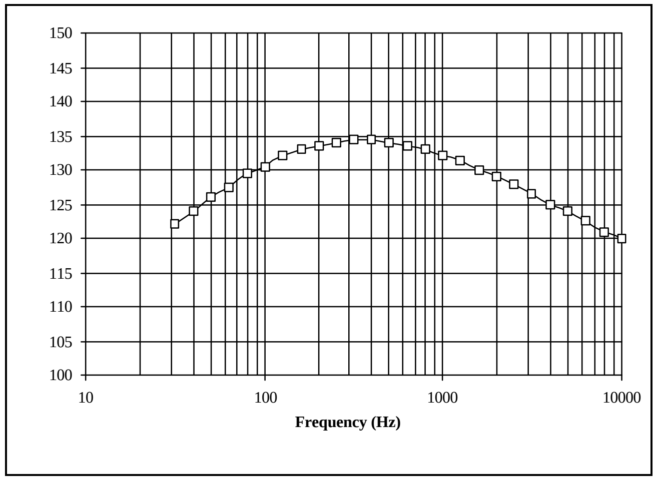

Figure 1 - Typical Acoustic Noise Requirement

In random vibration tests, the component is mounted to a test fixture in a manner which simulates the planned attachment to the spacecraft structure. The fixture is then mounted directly onto an electrodynamic shaker, or to an auxiliary slip table. The fixture and the slip table are heavy, thick metal structures designed to be mechanically stiff, with their natural frequencies well above the test frequency range. A typical random vibration input spectrum is shown in Figure 2. The level is in units of G^2/Hz, and it covers the frequency range from 20 to 2,000 Hz.

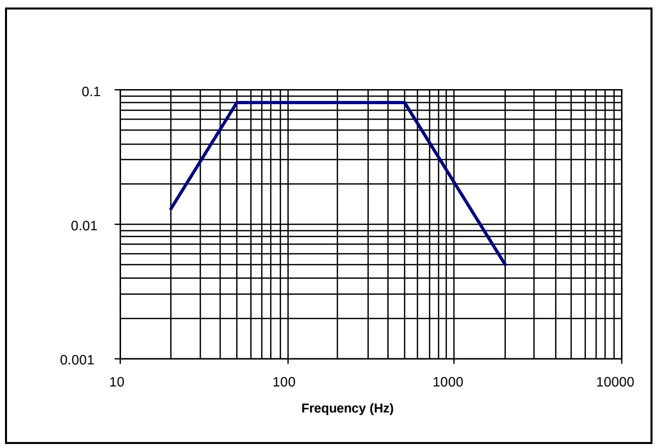

Figure 2 - Typical Random Vibration Spectrum

2.1 Comparisons Between Acoustic and Random Vibration

One of the fundamental differences between acoustic noise excitation and random vibration is the manner in which forces are applied.

In random vibration, the component is driven at its mounting location or base. The component responds to the vibration in a manner consistent with the spring rate of the mounting structure and its mass distribution. In acoustic vibration, the input is distributed across the surface area of the component, which is usually supported by a low spring rate structure such as a bungie cord. The component base or mounting surface is not connected to any structure.

Different mode shapes result from each type of vibration. Random vibration is useful for exciting normal spring mass type structures and acoustic vibration is especially effective at exciting flat plate resonant modes. The difference in the location of actuation has significant impact on the effectiveness of the two tests because of differences in the vibration frequency, magnitude, and response mode shapes.

2.1.1 Vibration Frequency

Acoustic excitation is often referred to as a "high frequency test" because, as previously mentioned, it covers the frequency range from 30 to 10,000 Hz. Random vibration is often considered a "low" or "mid" frequency test because excitation occurs typically in the range from 20 to 2,000 Hz. At frequencies above 2,000 Hz, the acoustic noise field contains considerable energy, while random vibration occurs only as a result of harmonics.

The higher frequency content in acoustic vibration is also due to differences in the input location. Since random vibration is input at the base of a component, excitation frequencies above the fundamental mode begin to be attenuated. At higher frequencies, more vibration modes from the initial input become filtered out. For acoustic vibration, the input is along the surface of the structure. High frequency energy is not attenuated because no "soft spring" low pass filter exists between the structure and the excitation source.

2.1.2 Energy Input

Acoustic vibration and random vibration tests impart different amounts of energy into different components depending upon the configuration. Acoustic energy is transmitted to the component though its surface area, such that a larger area will cause more energy to be imparted. Random vibration is input into the component from its base, and is therefore independent of surface area.

The test that will impart more energy to the component is a function of the surface area to mass ratio (area/mass) of the component. If the component has a low area/mass, random vibration will impart more energy, while acoustic vibration will dominate if a high area/mass ratio exists. A method to determine if the area/mass is sufficient to warrant an acoustic test is described later.

2.1.3 Vibration Mode Shapes

Acoustic and random vibration produce different mode shapes in the same component. This is because the location of the input force is different, and because the dominant frequency range is different.

Random vibration is best for exciting typical spring-mass types of modes. The input is through the component mounting structure, which effectively behaves like a spring. Acoustic excitation is best for simultaneously driving multiple modes of a plate-like structure, with little or no attenuation of high frequency dynamics.

2.2 Selecting Acoustic or Random Tests for a Component

When developing a test program for spacecraft, it is necessary to determine whether there should be an acoustic or random vibration test for each component. Several criteria must be considered when making such a decision.

First, frequency sensitivity of the component must be established. While many subsystems are not sensitive to frequencies above 2,000 Hz, those that do respond above this threshold cannot be tested by random vibration, but must instead be tested with acoustic noise. In these cases, decisions must be made regarding precisely how to conduct the acoustic test. The problem is easy for high area-to-mass components, which can simply be suspended with bungie cords within a reverberant acoustic chamber and directly "hit" with the acoustic source.

Low area/mass components are somewhat more problematic, as the vibration energy input should come through a base or mounting structure in the same manner as random vibration. This is because, when incident acoustic energy excites a spacecraft structure, high frequency random vibration is passed through the structure to mounted components.

To simulate this in an acoustic trial, the component should be mounted on a plate. The area distribution and dynamic characteristics of the plate must be similar to the spacecraft structure, so that a "flight-like" vibration environment is imparted to the unit under test. The plate should then be excited by acoustic energy, which will be passed along to the component in the form of high frequency random vibration. Figure 3 shows a test setup as described.

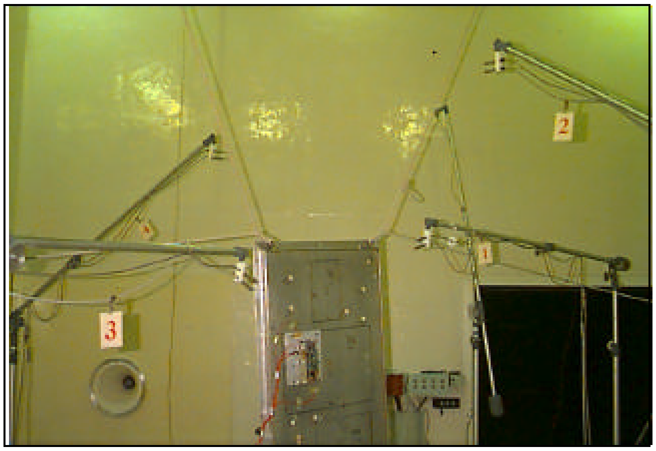

Figure 3 - Acoustic Test with Component Attached to Plate

Below 2,000 Hz, low area/mass components can be tested with random vibration only. The random vibration input curve should be the combined acoustic and random response of the spacecraft structure at the component interface. One exception to this rule occurs when a subsystem contains parts that are sensitive to acoustic noise, but which have natural frequencies greater than that of the subsystem. In such cases, random vibration in the sensitive parts would be filtered out by the lower subsystem fundamental frequency. The parts would not be excited unless both acoustic and random vibration tests were conducted.

2.2.1 Surface Area to Mass Ratio

The most important criterion for determining if a random vibration or acoustic trial should be performed is the area-to-mass ratio of the component. High area-to-mass components are more susceptible to acoustic testing, while low area/mass components favor random vibration testing.

The "break even" area/mass ratio, representing the regime in which both acoustic and random vibration tests induce equal stochastic acceleration responses, can be calculated analytically for a single degree of freedom system. A schematic of an example component is shown in Figure 4. The example component is a simple mass, spring and damper system, having a natural frequency (f_n) of 200 Hz, a mass of 100 lb., and a "Q" of 10. The term "Q" stands for quality factor, and represents the system mechanical gain during forced vibration at the system natural frequency. In this case, if the base is vibrated with a sinusoidal input at 200 Hz and a peak input acceleration of one G, the mass will respond with sinusoidal vibration at 200 Hz, and a peak acceleration of 10 Gs.

Typical launch vehicle acoustic and random vibration environments, provided in Figures 1 and 2 respectively, are used for this calculation. The objective is to solve for the component surface area where acoustic and random vibration tests are equally effective. From this, the break-even area/mass ratio can be calculated. Above this ratio the acoustic test will be more severe, while below this ratio the random vibration test will dominate.

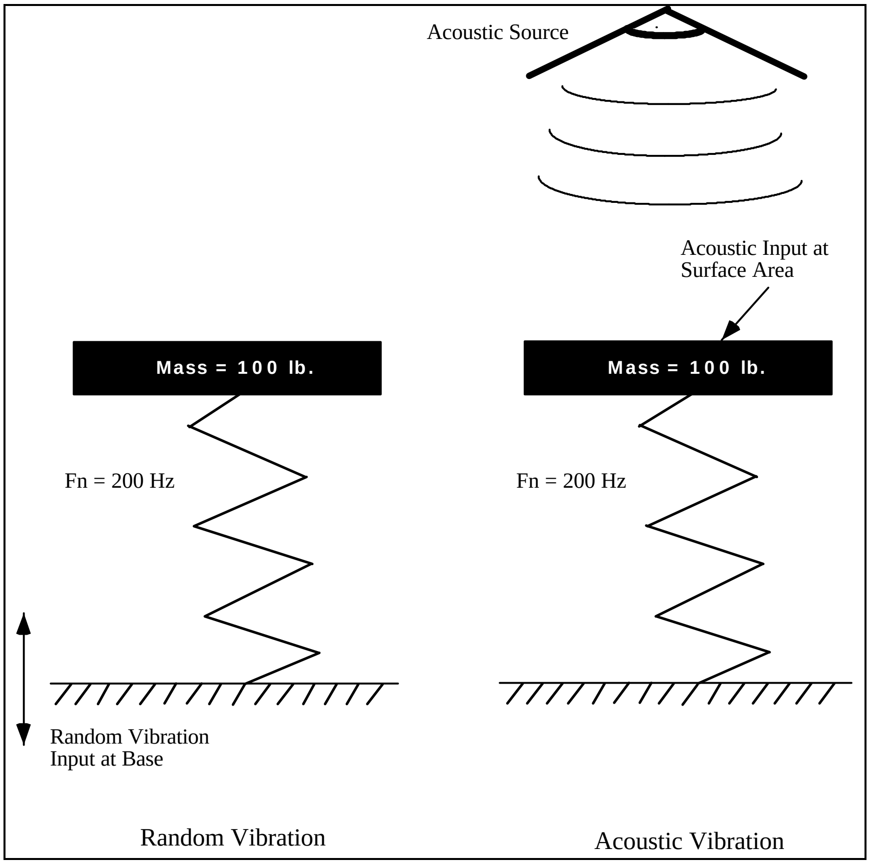

Figure 4 - Simple Component Under Acoustic and Random Vibration

2.2.2 Random Vibration Response

The response of our sample component can be calculated using Miles' equation, in conjunction with the techniques of Bibliography entry number 4.

Miles Equation: $G(rms) = (\pi/2 \times PSD \times f_n \times Q)^{1/2}$

where: $G(rms) = 1\sigma$ stochastic acceleration response
$PSD = 0.08\ G^2/Hz$ (from Figure 2 at 200 Hz)
$f_n = 200$ Hz
$Q = 10$

For our model component:

$$G(rms) = (\pi/2 \times 0.08\ G^2/Hz \times 200\ Hz \times 10)^{1/2}$$
$$= 16\ G_{rms}$$

2.2.3 Response to Acoustic Noise

To obtain the component response due to acoustic excitation, the first value to be calculated is the sound pressure spectral density (P_S) at the natural frequency (f_n) of the component, as follows.

P_S is defined as:

$$P_S = P^2/\Delta f \quad (lb./in.^2)^2/Hz$$

and is calculated from:

$$Ps = \frac{(2.9 \times 10^{-9})^2 \times 10^{dB/10}}{0.231 \times f_n}$$

For our sample component, P_S is calculated using $f_n = 200$ Hz and the decibel sound pressure at 200 Hz (= 133.5 dB), as follows:

$$Ps = \frac{(2.9 \times 10^{-9})^2 \times 10^{133.5/10}}{0.231 \times 200}$$

$$= 4.1 \times 10^{-6} \quad (lb./in.^2)^2/Hz$$

The root-mean-square pressure P(rms) is then calculated (again using Miles' equation) as follows:

$$P(rms) = (\pi/2 \times P_s \times f_n \times Q)^{1/2}$$
$$= (\pi/2 \times 4.1 \times 10^{-6}((lb./in.^2)^2/Hz) \times 200\ Hz \times 10)^{1/2}$$
$$= 0.11(lb./in.^2)_{rms}$$

2.2.4 Determining "Break Even" Surface Area

The random vibration response of our example component was found to be 16 G_{rms}. The rms pressure generated by acoustic vibration was found to be 0.11(lb./in.^{2}) rms. The component surface area, such that acoustic noise will create the same response as random vibration, is calculated by dividing the random vibration response force by the acoustic noise response pressure, as follows:

$$16\ G_{rms} \times 100\ lb / 0.11(lb./in.^2)_{rms} = 14{,}500\ in.^2$$

If the component has a surface area greater than 14,500 in.^{2}, then the acoustic vibration test will produce a higher response, and will subsequently be more effective. If the component has a surface area less than 14,500 in.^{2}, the random vibration test will be more effective. If the component has a surface area in the proximity of 14,500 in.^{2}, neither test can be determined to be more effective than the other, and it may be necessary to conduct both.

For the example component, the "break even" area/mass ratio is 145 in.^{2}/lb, calculated as follows.

$$14{,}500\ in.^2 / 100\ lb. = 145\ in.^2/lb.$$

When several calculations of this type are performed, it becomes apparent that the break even point is commonly around 150 in.^{2}/lb. for the spacecraft launch environment. This number varies for different launch vehicles, spacecraft and components, so calculations should always be performed. However, 150 in.^{2}/lb. is a good "order of magnitude" number for preliminary project planning estimates. An experienced dynamics engineer should always be consulted before test plans are finalized.

3.0 Acoustic vs. Random Vibration Testing at the Spacecraft Level

Acoustic and random vibration at the spacecraft level is very similar to that at the component level. For acoustic testing, the major difference is the manner in which the spacecraft is mounted. Usually it sits directly on the chamber floor or on a dolly used for spacecraft handling. For random vibration, the spacecraft is mounted to a shaker at the launch vehicle interface, and is vibrated in the same manner as a component. Clearly, the facility to test a spacecraft may need to be larger than for component testing.

Spacecraft often contain parts that are susceptible to both random vibration and to acoustic noise. Therefore, if at all possible, spacecraft should undergo both types of tests to ensure that all potential failure modes are screened. If this is not possible, then an effectiveness ranking should be performed to select the single test that excites the more dominant failure modes.

To select between an acoustic or random vibration test at the spacecraft level, it is necessary to determine where failures are expected to occur. While the majority of components should have been tested already for either acoustic or random vibration, little if any of the interconnecting structure and cabling between components will have been subjected to these trials. These sections of the spacecraft must be evaluated to determine if an acoustic test or random vibration test is more effective. A list of items that have not been tested for each type of vibration should be generated. Then the test that excites the most important untested potential failure modes should be chosen. This decision is rather subjective, based on qualitative reasoning more than on quantitative analysis.

The entire test plan, including both component and spacecraft level testing, should be developed at the beginning of the program. If only one spacecraft level test is to be performed, then subsystem testing should be tailored accordingly to ensure that all subsystems are qualified and that all potential failure modes are covered. In this way, the component and spacecraft test programs can complement each other, ultimately reducing program cost.

4.0 Comparison with Historic Data

Components with high area/mass ratio are usually associated with high gain antennas (HGAs) and solar panels. The Cassini HGA has a surface area to mass ratio of 175 in.^{2}/lb. Typical HGAs and solar panels range from 150 to 300 in.^{2}/lb. Electrical and mechanical components are usually below 100 in.^{2}/lb.

As expected, historical data shows that there are more failures of high area/mass ratio components due to acoustic testing, and more failures of low area/mass ratio components due to random vibration testing. This finding is illustrated in Table 1, which provides results of a study of 21 vibration related problems. Of these, 7 were associated with high area/mass hardware, and occurred during acoustic testing.

Table 1 - Historic Data of Random and Acoustic Vibration Test Results

Project	Subsystem	Problems found by following test:	
		Acoustic	Random Vibration
3AAL	System		X
3AAL	System		X
Viking	Power		X
Viking	Propulsion		X
Viking	Antenna	X	
Viking	Antenna	X	
Voyager	Antenna	X	
ACES	System	X	
ACES	System	X	
Cassini	Instrument		X
Galileo	Antenna	X	
Galileo	Antenna	X	
Galileo	Antenna	X	
Galileo	Instrument	X	
Mars Observer	Telecom	X	
Topex/Poseidon	Propulsion		X
Topex/Poseidon	Propulsion		X
Topex/Poseidon	Instrument		X
Topex/Poseidon	Instrument		X
Topex/Poseidon	System	X	
Topex/Poseidon	System	X	

5.0 Conclusions

A methodology has been developed for optimizing acoustic and random vibration in the environmental test program to reduce cost and schedule, without incurring undue risk to the hardware. Depending on the surface area, mass, and geometry of the test object, one vibration test is normally more effective as a failure screening mechanism. Random vibration is found to be more effective in spring-mass systems with input frequencies ranging from 20 to 2,000 Hz, whereas acoustic testing is more effective for plate-like structures with input frequencies ranging from 30 to 10,000 Hz.

The area-to-mass ratio of a test object is important in the selection of a vibration test method. Acoustic testing is shown to be more effective for high area-to-mass components, while random vibration testing is more effective for low area/mass components. The “break even” area/mass ratio, representing the regime in which both tests are equally effective, has been calculated analytically for a single degree of freedom system. It has been shown that, when area/mass exceeds 150 in.^{2}/lb, acoustic noise testing is usually more effective, while random vibration testing is most effective for lower area/mass ratios.

Spacecraft level testing is designed to be a final check on the entire assembly, including parts that were not previously tested. These parts include untested or under-tested subsystems, interconnecting cables and major spacecraft structural elements. Thus, to optimize vibration testing at the spacecraft level, the prior qualification status of subcomponents must be considered, along with the need to effectively screen all potential spacecraft failure modes. Concurrent planning of both subsystem and spacecraft tests helps to optimize this process.

6.0 Acknowledgments

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