NOT MEASUREMENT SENSITIVE

National Aeronautics and Space Administration

NASA-STD-7001
JUNE 21, 1996

# PAYLOAD VIBROACOUSTIC TEST CRITERIA

## NASA TECHNICAL STANDARD

# FOREWORD

This standard is approved for use by NASA Headquarters and all Field Centers and is designed to provide a common framework for consistent practices across NASA programs.

In early 1993, a concerted effort was initiated within the NASA engineering community to develop Agency-wide standards for hardware verification in four disciplines: fracture control, loads definition, vibroacoustics, and ground support equipment. These efforts resulted from a recommendation of the NASA Engineering Management Council (EMC), which had encouraged a similar activity in 1992 for structural factors of safety. That activity produced a white paper on factors of safety for the EMC that was well received and led to the expansion of the effort to the other four disciplines.

The exchange of flight hardware in multicenter projects mandates that qualification and acceptance test practices be consistent across the Agency. Recent experience in these kinds of projects, where different field installation policies are invoked, has necessitated case-by-case negotiations on testing requirements and special evaluations of qualification status. This approach may result in technical compromises and certainly incurs unnecessary costs and delays in project progress. The goal of a single NASA policy for vibroacoustics verification test practices will do much to streamline the intercenter research and development process.

The Vibroacoustics Standards Panel was assembled by the Goddard Space Flight Center (GSFC), which was named to chair and organize the activity. Members were nominated by EMC representatives of the Centers and guidance to the Panel by the EMC was broad and non-specific. Essentially, the EMC expected the Panel to develop and execute a charter that would serve as a directive to generate guidelines for the development of a standards document that would address the long standing divergence of practices within the Agency regarding the vibroacoustic qualification and acceptance testing of payload hardware. As a result, the Panel produced a white paper that contains a resolution of the divergent issues and the necessary core information to develop the subject standards document.

Requests for information, corrections, or additions to this standard should be directed to the Structures and Dynamics Laboratory, Mail Code ED21, Marshall Space Flight Center, AL, 35812. Requests for additional copies of this standard should be sent to NASA Engineering Standards, EL02, MSFC, AL 35812 (telephone 205-544-2448).

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# PAYLOAD VIBROACOUSTIC TEST CRITERIA

## 1. SCOPE

1.1 Scope. The term vibroacoustics is defined as an environment induced by high-intensity acoustic noise associated with various segments of the flight profile. It manifests itself throughout the payload in the form of transmitted acoustic excitation and as structure-borne random vibration. Therefore, the standard is to specifically address the acoustic and random vibration environments and test levels.

1.2 Purpose. The primary objective of this standard is to establish a uniform usage of test factors in the vibroacoustic verification process for spaceflight payload hardware. The standard provides test factors for verification of payload hardware for prototype, protoflight, and flight acceptance programs. In addition, minimum workmanship test levels are included. With the exception of minimum workmanship test levels, the test levels are given in relation to the "maximum expected flight level" (MEFL). Although the major emphasis of the standard is on test levels, the standard also covers the subjects of test duration, test control tolerances, data analysis, test tailoring, payload fill effects, and analysis methods.

1.3 Applicability. This standard recommends engineering practices for NASA programs and projects. It may be cited in contracts and program documents as a technical requirement or as a reference for guidance. Determining the suitability of this standard and its provisions is the responsibility of program/project management and the performing organization. Individual provisions of this standard may be tailored (i.e., modified or deleted) by contract or program specifications to meet specific program/project needs and constraints.

The standard applies only to spaceflight payload hardware. Launch vehicles, payloads launched by sounding rockets, aircraft and balloons, and ground support equipment are excluded. The levels of assembly for which the standard is applicable are the payload, subsystem, and component levels as specifically identified or as judged to be appropriate. A payload is defined as an assemblage of subsystems designed to perform a specified mission in space; a subsystem is defined as a functional subdivision of a payload consisting of two or more components; and a component is defined as a functional subdivision of a subsystem and is generally a self-contained combination of items performing a function necessary for the subsystem's operation. The standard is applicable to the full range of payload hardware programs including prototype, protoflight, follow-on, spare, and reflight.

The levels and methods set forth herein shall form the basis for developing project-specific requirements for all new payload projects. Deviations to and tailoring of the standard for the project's specific applications shall be reviewed and approved by the project manager and the appropriate engineering support organization. As much as possible, these variances shall be identified early in the project's life cycle, e.g., prior to phase C/D implementation. A permanent record shall be maintained by the project's quality assurance organization. The standard shall be applicable principally to Class A, B, and C payloads, while Class D payloads may utilize tailoring as stated in 4.3.6.

1.4 Summary of verification test requirements.

| | |
|---|---|
| Maximum expected flight level (MEFL) | 95%/50% Probability Level |
| Test levels | |
| Prototype/protoflight qualification | MEFL + 3 dB |
| Flight acceptance | MEFL - 3 dB |
| Minimum vibration workmanship test | 6.8 $g_{rms}$ |
| Minimum acoustic workmanship test | 138 dB |
| Test durations | |
| Prototype qualification, single mission | 2 minutes |
| Prototype qualification, multiple (N) reflights | 2 + 0.5N minutes |
| Protoflight qualification | 1 minute |
| Flight acceptance | 1 minute |
| Payload classification applicability | Classes A, B, and C |

A minimum workmanship random vibration test specification shall be imposed on electrical, electronic, and electromechanical components weighing less than 50 kilograms (kg) (110 lb.). The spectrum is given in 4.2.3, Table I. When the workmanship test level exceeds the prototype/ protoflight and/or the flight acceptance levels, the test levels shall envelope the two spectra.

Random vibration test control tolerances on power spectral densities (PSD's) shall be ±3 decibels (dB). When the minimum workmanship test level governs in a prototype program, the tolerances shall be such that the acceptance test level never exceeds the qualification test level. The tolerance on composite root mean square (rms) accelerations shall be ±10 percent.

Acoustic test control tolerances on sound pressure levels (SPL's) shall be ±3 dB from 50 to 3000 hertz (Hz), with facility capability determining the tolerances below 50 Hz and above 3000 Hz. The tolerance on overall SPL's shall be ±1 dB.

## 2. APPLICABLE DOCUMENTS

2.1 General. The applicable documents cited in this standard are listed in this section only for reference. The specified technical requirements listed in the body of this document must be met whether or not the source document is listed in this section.

2.2 Government documents. The following Government documents form a part of this document to the extent specified herein. Unless otherwise specified, the issuances in effect on date of invitation for bids or request for proposals shall apply.

| | | |
|---|---|---|
| NASA-CR-173472 | - | *NASA Flight Electronics Environmental Stress Screening Survey,* E.J. Marian, Washington, DC, December 1983 |
| NASA TN-2158 | - | *Statistical Techniques for Describing Localized Vibratory Environments of Rocket Vehicles,* Robert E. Barrett |
| NASA-STD-5002 | - | *Load Analyses of Spacecraft and Payloads* |

(Unless otherwise indicated, copies of the above documents are available from any NASA Installation library or documentation repository.)

2.3 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issuances in effect on the date of invitation for bids or request for proposals shall apply.

| | | |
|---|---|---|
| Report No. 99S0650 | - | *Test Report for Acoustic and Structural Response Test Test of Generic Spacecraft/Nose Fairing Configurations,* M.A. Gehringer, B.H. Forssen, General Dynamics Space Systems Division, June 1, 1994 |
| | - | *NASA LeRC's Acoustic Fill Effect Test Program and Results,* W.O. Hughes and M.E. McNelis, NASA Lewis Research Center, J.E. Manning, Cambridge Collaborative Incorporated, Proceedings of the 15th Aerospace Testing Seminar, October 11-13, 1994 |
| CC Report 93-11-12349-01 | - | *Acoustic Fill Factor Report,* J.E. Manning, B.F. Hebert, K. Weissman, Cambridge Collaborative Incorporated, submitted to NASA Lewis Research Center, November 30, 1993 |
| CC Report 91-6-12104-1 | - | *Analysis and Evaluation of the Fill Factor,* J.E. Manning, Cambridge Collaborative Incorporated, submitted to NASA Lewis Research Center, January 28, 1991 |
| | - | *Force Specifications for Extremal Dual Controlled Vibration Tests,* Terry Scharton, 61st Shock and Vibration Symposium, Los Angeles, CA, October 1990 |
| | - | *Development of the Force Envelope for an Acceleration/Force Extremal Controlled Vibration Test,* D. Smallwood, 61st Shock and Vibration Symposium, Los Angeles, CA, October 1990 |
| | - | *Force Limited Vibration Testing at JPL,* Terry Scharton, IES/Aerospace Corporation, 14th Aerospace Testing Seminar, Manhattan Beach, CA, March 1993 |
| | - | *Vibration Test Force Limits Derived From Frequency Shift Method,* Terry Scharton, AIAA 35th Structures, Structural Dynamics, and Materials Conference, Hilton Head, SC, April 18-20, 1994 |
| IES-RP-DTE012.1 | - | *Handbook for Dynamic Data Acquisition and Analysis,* Institute of Environmental Sciences |

Sandia Monograph SCR-607 - *Factors for One-Sided Tolerance Limits and for Variables Sampling Plans*, D.B. Owen, March 1963

- *Statistics of Extremes*, E.J. Gumbel, Columbia University Press, 1958

- *Structural Acoustics Using Statistical Energy Analysis*, presented by J.E. Manning, Cambridge Collaborative Incorporated, at NASA Lewis Research Center, November 7, 1988

- *Statistical Energy Analysis of Dynamical Systems: Theory and Applications*, by R.H. Lyon, MIT Press, Cambridge, MA, 1975

(Unless otherwise indicated, copies of the above documents are available from any NASA Installation library or documentation repository.)

2.4 Order of precedence. Where this document is adopted or imposed by contract on a program or project, the technical guidelines of this document take precedence, in the case of conflict, over the technical guidelines cited in other referenced documents. This standard does not apply to payload programs approved prior to the date of this document. Also, this standard does not address safety considerations that are covered thoroughly in other documents; but if a conflict arises, safety shall always take precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

## 3. DEFINITIONS

None (Abbreviations and Acronyms are found in 5.3.)

## 4. REQUIREMENTS

### 4.1 Methods and assumptions related to use of verification tests.

4.1.1 Purpose of tests and test factors. The purpose of testing with test factors is to prove design performance at the MEFL, plus margin for uncertainty, to demonstrate that hardware is acceptable for flight, and to verify that adequate workmanship exists in the construction of the hardware. Tests are critical for high frequency sensitive equipment because the complexity of design details of such hardware seriously limits the use of analysis. Also, tests are not intended to produce loads that exceed design requirements or to introduce unrealistic modes of failure. When defining test factors, various sources of uncertainty must be considered such as the following:

a. Material properties variations (strength and life)

b. Fabrication, variations (within specification)

c. Load variations

d. Test configuration fidelity

e. Environment specification method fidelity

f. Design maturity uncertainty

g. Cost, schedule, and risk

4.2 Test levels.

4.2.1 Prototype and protoflight.

a. Prototype tests, also referred to as qualification tests, are performed on dedicated test hardware which is produced from the same drawings and using the same materials, tooling, manufacturing processes, inspection methods, and level of personnel competency as used for the flight hardware. Prototype tests demonstrate, with margin, the design adequacy of the hardware for its intended mission use.

b. Protoflight tests are performed on flight and flight spare hardware where dedicated test hardware for prototype testing does not exist. The protoflight testing of flight spares would occur only when the first item built is declared to be a spare. Protoflight tests serve the purpose of both the prototype and flight acceptance tests. That is, the tests assess the design adequacy of the hardware, demonstrate the satisfactory performance of the flight hardware relative to the expected environment, and reveal inadequacies in workmanship and material integrity.

c. Acoustic prototype and protoflight tests shall be conducted at levels that are an envelope of the maximum expected flight level plus 3 dB and the minimum workmanship levels defined in 4.2.3. Random vibration prototype and protoflight tests shall be conducted at levels that envelope the maximum expected flight level plus 3 dB and the minimum workmanship levels as defined in Table I, 4.2.3. Methods for determining the maximum expected flight level are described in 4.4.

4.2.2 Acceptance testing. Acceptance tests are conducted to demonstrate satisfactory performance of flight systems relative to the expected environment and to reveal inadequacies in workmanship and material integrity. The tests are performed for hardware that has been qualified by prototype or protoflight testing. Flight acceptance units include follow-on spacecraft hardware and flight spares that are identical in design and material configuration to the qualified article.

Acoustic flight unit acceptance tests are conducted at levels that are an envelope of the maximum expected flight level minus 3 dB and the minimum acoustic test spectrum defined in 4.2.3. Random vibration flight unit acceptance tests are conducted at levels that envelope the maximum expected flight level minus 3 dB and the minimum workmanship levels as defined in Table I, 4.2.3.

4.2.3 Workmanship. Workmanship random vibration testing is performed to identify latent defects and manufacturing flaws in electrical, electronic, and electromechanical hardware at the component level. Care should be exercised not to apply these criteria, however, to highly sensitive optical components and sensors that could be damaged by the stated levels.

For components weighing less than 50 kg (110 pounds), the spectrum shown in Table I shall be used as a minimum vibration test specification. This spectrum is within the envelope recommended in NASA CR-173472. The component shall be subjected to the random vibration test along each of three orthogonal axes for the appropriate duration as specified in 4.3.3.

TABLE I. Component Minimum Workmanship Random Vibration Test Levels

| | | |
|---|---|---|
| 20 Hz | @ | 0.01 $g^2$/Hz |
| 20 to 80 Hz | @ | +3 dB/oct |
| 80 to 500 Hz | @ | 0.04 $g^2$/Hz |
| 500 to 2000 Hz | @ | -3 dB/oct |
| 2000 Hz | @ | 0.01 $g^2$/Hz |
| Overall Level | = | 6.8 $g_{rms}$ |

Components shall be mounted to the shaker using the same mounting hardware and configuration that was used in the vibration qualification test. For components mounted on isolators or highly compliant mounting hardware, adequate workmanship testing may not be achieved in the flight configuration. In this case, the component may be hard-mounted to the shaker, but the qualification of the component must be assessed to ensure that the workmanship test did not induce higher responses in the component than the qualification test. The hardware may have to be requalified in the hard-mounted configuration.

Workmanship acoustic testing shall be performed for all hardware levels of assembly described in 4.3.1. The minimum acoustic test level shall be 138 dB overall. The test spectrum shape shall be identical to the expected flight spectrum including fill effects. Durations of testing are specified in 4.3.3.

4.2.4 Acoustic fill effect. The understanding of acoustic fill effects for specifying an acoustic environment is important for payload hardware design and testing. The fill effect is the term used to describe the changes in the interior SPL of an expendable launch vehicle's payload fairing or the Space Shuttle's cargo bay caused by the presence of a payload. This increase in acoustic pressure levels due to payload fill effects has been measured in tests (refer to Report No. 99S0650 and to *NASA LeRC's Acoustic Fill Effect Test Program and Results*) and predicted theoretically (refer to CC Report 93-11-12349-01 and CC Report 91-6-12104-1).

The fill effect has the following characteristics:

a. The fill effect is greater for lower frequencies.

b. The fill effect is greater for larger payload volumes.

c. The fill effect is greater for smaller gap distances between the payload wall and the fairing/cargo bay wall.

The acoustic fill effect shall be implemented as follows:

1. Calculate the payload volume, $Vol_{payload}$, in a zone of interest.

2. Calculate the empty fairing/cargo bay volume (with the same length as the payload zone), $Vol_{empty}$.

3. Use the results of steps 1 and 2 to calculate the ratio of the payload volume to the empty fairing/cargo bay volume, $Vol_{ratio}$.

$$Vol_{ratio} = \frac{Vol_{payload}}{Vol_{empty}}$$

4. Calculate an average gap distance ($H_{gap}$) between the payload surface and the fairing/cargo bay surface.

5. Use the following equation to calculate the acoustic fill effect in dB, as a function of frequency (f).

$$\text{FillFactor (dB)} = 10\,\text{Log}_{10}\left[\frac{\left(1+\dfrac{c_a}{2\,f\,H_{gap}}\right)}{1+\left(\dfrac{c_a}{2\,f\,H_{gap}}\right)\left(1-Vol_{ratio}\right)}\right]$$

where:

$c_a$ is the speed of sound in air (typically 344.4 meters/second).

f is the one-third octave band center frequency (Hz).

$H_{gap}$ is the gap distance between the payload and the fairing/cargo bay wall.

$Vol_{ratio}$ is the volume ratio of the payload volume to the empty fairing/cargo bay volume, for a given payload zone length.

6. Add the fill effect results of step 5 to the acoustic levels specified for the empty fairing/cargo bay. (Example: 4 dB fill effect + 130 dB empty SPL = 134 filled SPL).

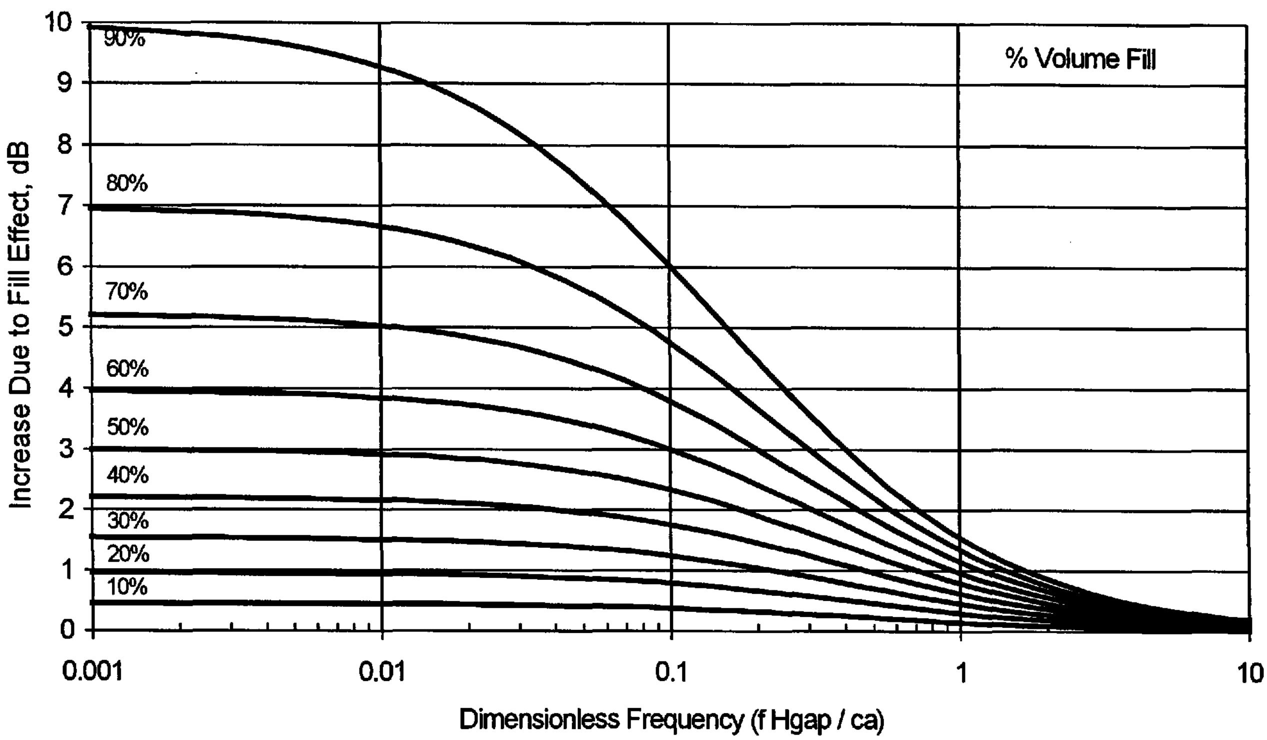


FIGURE 1. Fill Factor Design Chart

Figure 1 is a design chart which illustrates the fill effect obtained from the fill effect equation versus a dimensionless frequency (f $H_{gap}$ / $c_a$), for various $Vol_{ratio}$.

The following fill effect considerations should be noted:

a. The fill effect should only be applied to payloads which exhibit extensive volumetric displacements. If the payload is highly unsymmetric or has discrete structures or appendages, then engineering judgment should be utilized in applying the fill effect.

b. Fill effects greater than those predicted are possible in individual one-third octave bands at low frequencies. These exceedances are due to unique payload geometries which cause shifting of acoustic modes (refer to *NASA LeRC's Acoustic Fill Effect Test Program and Results*). If the payload structure is acoustically sensitive at low frequencies, then further analysis such as acoustic finite element analysis may be warranted.

c. Because of the unique acoustic modes created for each payload and fairing/cargo bay combination, caution should be used when interpreting flight data fill effects and applying them to another payload and fairing/cargo bay combination, which is geometrically dissimilar.

4.3 Test methods and specifications.

4.3.1 Acoustic tests. Acoustic tests are generally required at the entire spacecraft assembly level. In addition, aerospace hardware requiring acoustic testing for vibroacoustic verification are usually large area-to-weight ratio structures, such as skin panels, reflectors, dish antennae, and solar panels that respond significantly to the direct impingement of the acoustic environment. Two types of components require both vibration and acoustic testing: (1) those components which are mounted with vibration isolators, and (2) those components which consist of significant piece parts with first resonant frequencies greater than 2000 Hz. Vibration isolators attenuate the high frequency mechanical vibration below the level resulting from direct acoustic impingement; therefore, these components should be reviewed on a case-by-case basis, and a test program should be implemented that also satisfies minimum workmanship criteria. Also, many electronic black boxes and glass components have microstructural elements that are resonant above 2000 Hz, which is generally the limitation of most large electrodynamic shakers. Acoustic testing shall be performed by controlling the SPL's (dB re 20 μPa) in 1/3-octave bands over the specified frequency range.

All payload structures and components requiring acoustic testing shall be subjected to broadband reverberant field testing. The acoustical random noise source shall have an approximate normal amplitude distribution. Test levels shall be determined using the methods described in 4.2.1 and 4.2.2, and the test tolerances to be adhered to are described in 4.3.4.

The reverberant field test chamber shall be of sufficient volume and dimensions to ensure that the insertion of a test specimen will not affect the generation and maintenance of a broadband diffuse sound field above 50 Hz. It is preferable that the chamber volume be at least 10 times the test specimen volume. If the test specimen is to be suspended, the suspension system should have a fundamental frequency of less than 25 Hz. The sound field in the proximity of each major surface of any test specimen that will be subjected to acoustic environments shall be determined by at least three microphones. The microphones shall be positioned around the test chamber at sufficient distance from all surfaces to avoid absorption and re-radiation effects. A distance from any surface of at least 1/4 of the wavelength of the lowest frequency of interest is recommended. In facilities where this cannot be achieved, the microphones shall be located in positions so as to be affected as little as possible by surface effects. The control measurements shall be averaged to determine the sound field.

With the specimen in the test chamber, the acoustic spectrum shall be shaped at a level approximately 6 dB less than the specification. The time required to shape the spectrum shall be minimized to avoid possible fatigue of the test specimen. After completion of the spectrum shaping, the SPL shall be increased to the specified value, and the test will then commence. As an alternative to reducing the SPL while shaping the spectrum, a dummy specimen may be positioned in the test chamber and the spectrum shaped at the test level. When the spectrum shaping has been completed, the dummy specimen shall be replaced by the test specimen, and the test will then begin.

4.3.2 <u>Random vibration tests</u>. Random vibration testing is required for essentially all electrical, electronic, and electromechanical components and mechanisms. Exceptions are large area-to-weight structures, which may be subjected to acoustic testing in lieu of random vibration, and hardware not practical to vibrate at the component level such as structures, electrical cabling, plumbing lines, blankets, etc., that may be deferred to the system level vibration or acoustic test. Compact payloads weighing less than 450 kg (1000 pounds) shall be subjected to system level random vibration testing unless an analysis shows that the payload responses are clearly dominated by the direct acoustic environment.

The test specimen shall be subjected to random vibration with a Gaussian amplitude distribution in each of three orthogonal axes. Random vibration testing shall be performed by controlling the acceleration spectral density ($g^2$/Hz) in the frequency range from 20 to 2000 Hz. The spectrum shall be within the test tolerance specified in 4.3.4.

The control accelerometer(s) shall be mounted on the test fixture near the attachment points. If more than one control accelerometer is used, the test levels may be controlled using either an averaging or an extremal control scheme; but the controller must be consistent with the test requirement derivation. The test fixture shall be subjected to a bare resonance survey up to 2000 Hz prior to the start of testing. If practical, the fixture shall have no resonances within the test frequency range. The test specimen shall be mounted to the fixture via its flight or flight equivalent mounting attachments.

Notching of the acceleration spectral density input may be technically justified in certain cases to eliminate unrealistically high amplification resonant responses and the associated risk of failures which can occur in conventional vibration tests of aerospace hardware. For typical aerospace structures, the mechanical impedance of the test item and the flight mounting structure are comparable so that the combined motion involves modest interface forces and little amplification. However, the mounting of the test item on a vibration fixture, with an effectively infinite impedance compared to the test item, results in high interface forces and often severely overtests the hardware at its resonances. This test artifact can be eliminated by limiting the interface forces in the test to that predicted for flight.

Force limiting provides a rational and economical solution to the overtesting problem associated with hard mounting of test items, while still providing high confidence in the capability of the hardware to survive the mission vibroacoustic environments. The theory and methodology for implementing force limiting, along with examples of specific applications, are presented in the following applicable Government documents:

*Force Specifications for Extremal Dual Controlled Vibration Tests*

*Development of the Force Envelope for an Acceleration/Force Extremal Controlled Vibration Test*

*Force Limited Vibration Testing at JPL*

*Vibration Test Force Limits Derived from Frequency Shift Method.*

4.3.3 <u>Test duration</u>. The durations for the tests described in 4.3.1 (acoustic tests) and 4.3.2 (random vibration tests) shall be as defined in the following paragraphs:

a. Qualification test duration.

1) Prototype. The prototype vibroacoustic qualification test durations shall be 2 minutes for the acoustic test and 2 minutes in each of the three orthogonal axes for the vibration test. If the flight hardware is to be reflown N times, the corresponding qualification test durations shall be 2 + 0.5N minutes.

2) Protoflight. The protoflight vibroacoustic qualification test durations shall be 1 minute for an acoustic test and 1 minute in each of the three orthogonal axes for a vibration test.

b. Acceptance test duration.

1) Prototype program. The vibroacoustic acceptance test durations, for a flight unit developed under the prototype concept, shall be 1 minute for an acoustic test and 1 minute in each of the three orthogonal axes for a vibration test.

2) Protoflight program. For follow-on spacecraft hardware and spares, the acceptance test durations shall be 1 minute for an acoustic test and 1 minute in each of the three orthogonal axes for a vibration test. There can be other situations (e.g., retesting of reflight hardware) where the test conditions will be defined by applying test tailoring (see 4.3.6).

4.3.4 <u>Test control tolerances</u>. For prototype program qualification and acceptance testing, the test control tolerances shall be such that the acceptance test level shall never exceed the qualification test level. The restricted use of tolerances is particularly critical when the minimum workmanship random vibration or acoustic specification governs any portion of the enveloped spectrum. With this stated condition, acceptable tolerances are as follows:

a. Vibration.

1) Composite RMS acceleration ........................................ ±10%

2) Acceleration spectral density (25 Hz or less frequency bandwidth resolution) ........................................ ±5%

3) Frequency ........................................ ±5%

4) Test duration ........................................ +10%, -0%

b. Acoustic.

1) Individual 1/3 octave band SPL's (50 to 3000 Hz) ........................................ ±3 dB

2) Overall sound pressure level ........................................ ±1 dB

3) Test duration ........................................ +10%, -0%

4) Facility capability will determine SPL tolerances below 50 Hz and above 3000 Hz.

4.3.5 <u>Test configuration</u>. A satisfactory verification test program shall adhere to the following test configuration methods:

a. During testing, the mechanical configuration of the test item shall be in a liftoff operational mode. The electrical operating mode shall be in accordance with the test plan. As a minimum requirement, the liftoff electrical condition shall be applied and monitored. Caution should be exercised so that full electrical stimulation for diagnostic purposes does not induce an unrealistic and damaging condition when combined with vibroacoustic exposure.

b. In mating the test article to the test fixture, a flight-type mounting (including vibration isolators if part of the design) and fasteners shall be used.

c. Components that are normally sealed shall be pressurized during the test to their prelaunch pressure.

d. For very large payloads, it may be impracticable (because of test facility limitations) to perform a random vibration test at the payload level of assembly. In that case, testing at the subsystem level of assembly shall be assessed.

e. For very large components, random vibration tests may have to be supplemented or replaced by an acoustic test due to test facility limitations.

f. The same test fixture should be used for both qualification and flight acceptance tests.

g. If the component level tests are not capable of inducing sufficient excitation to internal electric, electronic, and electromechanical devices to provide adequate workmanship verification, an environmental stress screening test program shall be conducted at lower levels of assembly (e.g., down to the board level, if necessary).

h. Vibroacoustic testing shall precede thermal-vacuum testing.

4.3.6 Test tailoring methods. This standard serves as a baseline that provides enough flexibility to allow tailoring to the needs of non-baseline situations. Nevertheless, all requirements of the standard shall be evaluated for each spacecraft application, and any specified tailoring shall be accompanied by a statement of the technical rationale for the tailoring. For example, random vibration test "notching" would be permitted on a case-by-case basis. That is, when it can be demonstrated that a specific hard-mounted shaker random vibration test would produce unrealistically high loads and/or responses, notching would be allowed. The logic used to develop a specific notching rationale shall be validated. Notching can be of the form of "force limiting" as discussed in 4.3.2. In addition to notching, there are other possible considerations that could dictate the use of test tailoring. Some of these possible considerations are as follows:

a. Class D payloads

b. Retesting of reflight hardware

c. Retesting due to limited redesign or rework

d. Storage

e. Fatigue damage concerns

f. Acoustic testing with payload fairing

g. Vibration testing with simulated support structure

h. Certain fragile, one-time use items such as instrument detector elements and batteries

4.4 Dynamic data acquisition and analysis. Methods are being published by the Institute of Environmental Sciences (IES) as an IES recommended practices handbook titled, *Handbook for Dynamic Data Acquisition and Analysis* (refer to IES-RP-DTE012.1). This document shall be used as a guideline for vibroacoustics data acquisition and analysis.

In practice, the maximum expected environment shall be based on:

a. The use of actual flight data scaled, if necessary, for differences in structure and acoustic environment

b. Ground test data scaled if necessary

c. Analytical predictions

d. A combination of both analytical and empirical methods

The flight data may be from the current flight system or from other flight systems if configuration variations are accounted for and properly scaled. A statistical approach shall not be used unless at least three data points are available, and engineering experience must be used to account for data and analysis uncertainties. Methods for vibroacoustic analysis are discussed in more detail in Appendix A.

Ground test operations and transportation vibroacoustic levels shall be controlled such that levels produced by these events shall not exceed the MEFL's. If it is not practicable to so constrain the ground test and/or transportation environments, they shall be considered as contributing to the design and test criteria.

# 5. NOTES

(This section contains information of a general or explanatory nature which may be helpful but is not mandatory.)

5.1 Intended use. This standard defines procedures for developing vibroacoustic test criteria for NASA payloads. It also presents methods for acceptance and qualification vibroacoustic testing, for statistical analysis of vibroacoustic data, and analysis methods for determining criteria. Minimum acoustic and random vibration workmanship test levels are specified. This standard only applies to NASA payloads and payload components and is not retroactive to the approval date.

5.2 Key word listing:

Acceptance test
Acoustic
Qualification test
Random vibration
Vibration
Vibroacoustic

## 5.3 Abbreviations and acronyms

| | | |
|---|---|---|
| a. | $c_a$ | speed of sound in air |
| b. | CF | correction factor |
| c. | dB | decibel |
| d. | EMC | Engineering Management Council |
| e. | f | frequency |
| f. | FEA | Finite Element Analysis |
| g. | g | acceleration due to gravity |
| h. | GSFC | Goddard Space Flight Center |
| i. | $H_{gap}$ | average gap distance |
| j. | Hz | hertz |
| k. | IES | Institute of Environmental Sciences |
| l. | kg | kilogram |
| m. | MEFL | maximum expected flight level |
| n. | μPa | micropascal |
| o. | N | number of reflights |
| p. | OASPL | overall sound pressure level |
| q. | oct | octave |
| r. | PSD | power spectral density |
| s. | rms | root mean square |
| t. | SEA | Statistical Energy Analysis |
| u. | SPL | sound pressure level |
| v. | VAPEPS | Vibroacoustic Payload Environmental Prediction System |
| w. | Vol | volume |

# APPENDIX A

# METHODS FOR VIBROACOUSTIC ANALYSES

## A.1 DATA ANALYSIS

A.1.1 Statistical standards. The vibroacoustic test levels are a function of the MEFL, as specified in 4.2.1 and 4.2.2, and are based upon statistically estimated spectral levels. It is recommended that a $P_{95/50}$ level be used to define the MEFL. The MEFL is the level that encompasses 95 percent of the data estimated with 50 percent confidence. These statistical estimates are to assume a log normal flight-to-flight variability, where the probability level is defined by

$$X_{95/50}(f) = \overline{X} + K\,S_x \qquad (1)$$

where $X_{95/50}$ is the percentile level corresponding to the $P_{95/50}$ level, $\overline{X}$ , and $S_x$ are the sample average and sample standard deviation, respectively, of the population of X(f ) = 10 $\log_{10}(y/y_{ref})$.

Here y is the spectral value of the vibroacoustic environment in $g^2$/Hz or $\mu Pa^2$ within a defined bandwidth and X is the spectral value in decibels referenced to 1 $g^2$/Hz or 1 $\mu Pa^2$ or any other desired reference. For example, 20 $\mu Pa^2$ is the accepted pressure squared reference for acoustic data. Note that aeroacoustic data are usually analyzed directly in dB's meaning no logarithmic conversion is necessary.

K is the "normal tolerance factor" for a selected "probability of not exceeding" (P%) of the population with a specific confidence coefficient (C%). K is a function of sample size and can be obtained from the Sandia Monograph SCR-607 and the *Statistics of Extremes*. In some cases, the log normal relationship for a $X_{95/50}$ level is adjusted to "best fit" independently calculated cumulative distributions. That is, an empirically derived correction factor (CF) can be used that multiplies the K factor such that the adjusted log normal relationship "best fits" the computed cumulative distribution at the larger or extreme percentile levels, that is,

$$X_{95/50}(f)\text{, in dB} = \overline{X} + CF\,(K\,S_x) \qquad (2)$$

For random vibration data, it may be preferable not to treat the data in dB form. That is, the population could be defined without a factor of 10 or consideration of a reference value, that is, $x = \log_{10} y$. In this case, appropriate simple adjustments can be made to the above expressions. The $X_{95/50}$ level exceedance of the statistical average level $\overline{X}$, in dB's, would become equal to 10 CF (K $S_x$) and the following modified expression would result:

$$Y_{95/50}(f)\text{, in } \frac{g^2}{Hz} = 10^{(\overline{X} + CF(S_x))} \qquad (3)$$

In this case, it must be recognized that the statistical terms $X_{95/50}$, $\bar{X}$, and $S_X$ are computed for a population defined as $x = \log_{10} y$.

Even though a log normal distribution or modified form thereof was selected as the baseline descriptor, based on the past experience of many investigators, this does not preclude the use of another distribution if it can be shown that it produces a satisfactory fit to the data (refer to NASA TN-2158).

In summary, the recommended procedure for statistical analysis is:

1. Calculate the common logarithm of the data (except for data already in dB form).

2. Calculate the mean and standard deviation of the logarithmic data.

3. Use the appropriate equation above to calculate the $P_{95/50}$ level.

## A.2 ANALYSIS METHODS

A.2.1 Statistical energy analysis. Statistical energy analysis (SEA) is a technique to analyze and predict the vibroacoustic response of a complex system by calculating the energy flow between subsystems. Manning (refer to NASA TN-2158) describes SEA as follows: "Statistical: take a statistical approach toward the calculation of resonance frequencies and mode shapes; Energy: use vibratory energy and power flow to derive equations of motion; Analysis: maintain parameter dependence to allow for design changes and improvements." Manning (refer to *Structural Acoustics Using Statistical Energy Analysis*) further defines the key SEA parameters to be: "modal density, damping loss factor, coupling loss factor and mechanical conductance." Further insight into SEA theory and applications may be found in *Structural Acoustics Using Statistical Energy Analysis* and *Statistical Energy Analysis of Dynamical Systems: Theory and Applications.*

SEA supplements the analyst's other tools such as empirical transfer functions (scaling) and finite element techniques. SEA covers the medium to high frequency range (typically 100 Hz and higher), whereas finite element analysis is suited to lower frequencies. Although scaling techniques may be accurate in the medium to high frequency range, a database of similar structure is not always available. Additionally, SEA modeling does not require the detailed structural modeling that finite element analysis does; therefore, SEA is both less expensive and quicker to perform than finite element analysis and easily allows for parameter redesign analysis.

SEA has been used to solve a variety of aerospace problems. Currently, the most widely used and most thoroughly validated SEA program is the Vibroacoustic Payload Environmental Prediction System (VAPEPS). In addition to its theoretical SEA predictions capability, VAPEPS also has the capability to make empirical predictions using flight and test databases. VAPEPS is currently used by most NASA Centers and most of the major aerospace contractors.

VAPEPS was originally developed by Lockheed Missile and Space Company under NASA GSFC funding. The Jet Propulsion Laboratory has operated the VAPEPS Management

Center since 1985. The objectives of the Center are to validate, maintain, and improve the prediction code, and to provide user support for the aerospace community. Sponsors of the VAPEPS Management Center have included NASA GSFC, US Air Force/Space Division, and currently NASA Lewis Research Center.

A.2.2 Finite element analysis. Finite element analysis (FEA) is a technique for analyzing complex structures by subdividing the structure into a finite number of smaller idealized structural elements that are interconnected through a grid system. The structural elements specify characteristics such as material properties, mass distribution, and external distributed loads while the grid system specifies characteristics such as structural geometry, external point loads, and boundary constraints. The elements, with their corresponding grid points, are then assembled into an overall structural model that can be used to analyze stress, vibration, or other static and dynamic structural characteristics.

FEA has its roots in aerospace applications. That is, aircraft companies did significant early work in this field in the 1950's and 1960's; and the first widely used FEA program, NASTRAN, was originally developed by NASA for the NASA/contractor community. Currently, there are a variety of commercially available FEA programs in addition to NASTRAN (e.g., among the most common are ANSYS, STARDYNE, ALGOR, COSMOS, and PATRAN).

To a large extent, vibroacoustic analysis has remained outside the realm of traditional FEA applications, mainly because of the relatively large effort required in modeling the acoustic field, which for most aerospace applications is induced by aeroacoustic rocket engine noise and aerodynamic flow. Instead, SEA techniques are often used to predict the structural vibroacoustic response. Although the SEA methodology is powerful, at lower frequencies (typically below 100 to 200 Hz), SEA's underlying assumptions regarding modal density render predictions that are invalid. But FEA techniques provide a powerful, alternative methodology for making vibroacoustic predictions in this frequency range. A sufficiently refined FEA model shall be able to make response predictions up to the 200 - 500 Hz region and thereby provide a very useful supplement, in the low- to mid-frequency region, to SEA predictions. Furthermore, many of the earlier FEA modeling difficulties are mitigated with the advent of robust, relatively inexpensive computers and the commercial availability of high quality FEA modeling programs. However, in the most widely available FEA codes, vibroacoustic loads are still not easily modeled and incorporated into the analysis codes.

# APPENDIX B

# VIBROACOUSTIC LOAD PREDICTION

## B.1 VIBROACOUSTIC LOADS

The structural design of hardware is affected by the vibroacoustic environment. Structural loads due to the vibroacoustic environment are a result of responses induced from direct acoustic impingement on the hardware and/or mechanically transmitted random vibration into the hardware. The acoustic and random vibration environments are specified as input levels that are launch vehicle and payload dependent. Analysis techniques simulating the induced levels are used to predict the resulting loads. More detailed information can be found in NASA-STD-5002, *Load Analyses of Spacecraft and Payloads.*

B.1.1 Combination of loads. The following has been excerpted from NASA-STD-5002, *Load Analyses of Spacecraft and Payloads:*

> ...the appropriate method of load combination is dependent on how the low frequency and the random vibration/acoustic design environments of the event are specified. Typically, the maximum levels are defined as requirements for a flight event, such as liftoff, even if these maxima do not necessarily occur at the same time. The relative timing of the transient and random vibration environments is unique for each launch vehicle, but simultaneous occurrence of maximum low frequency transient and maximum random vibration load is improbable. Therefore, a root-sum-square (RSS) approach is acceptable for combining the maximum low frequency and maximum random vibration loads for the liftoff flight event...

Additional information can be found in the above document.