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PAYLOAD VIBROACOUSTIC TEST CRITERIA

MEASUREMENT SYSTEM IDENTIFICATION:
METRIC/SI (ENGLISH)

DOCUMENT HISTORY LOG

	Document Revision	Approval Date	Description
Baseline		06-21-1996	Initial Release
Revision	A	01-20-2011	See description below:

General: Incorporated document into the standards template and made editorial changes.

Foreword: Moved background information to 5.3 and added 3rd paragraph that states: "This standard establishes a uniform usage of test factors in the vibroacoustic verification process for spaceflight payload hardware."

1.1: Added 2nd paragraph that states: "This standard defines ... approval date."

1.2: Changed 1st, 2nd, and 3rd paragraphs to conform to the standard template. Added last sentence to the 4th paragraph to read: "This standard does not apply to payload programs approved prior to the date of this document." Moved definitions for "payload," "subsystem," and "component" from the 5th paragraph to section 3.2.

1.2.1 Deleted "Deviations to and tailoring of this standard for the project's specific applications shall be reviewed and approved" and added 1.3 on Tailoring.

1.2.2 Changed ". . . these variances . . ." to ". . . tailoring . . .."

2: Changed text to conform to standard template.

2.2: Corrected "NASA TN-2158" to "NASA TN-D-2158" and its title; added document number "Sandia Monograph SCR-607" to "*Factors for One-Sided Tolerance Limits and for Variables Sampling Plans*." Also corrected in text where cited.

2.4: Revised text to conform to standard template.

3.1: Moved "Abbreviations and acronyms" from 5.3.

3.2: Added three definitions from 1.2.

4.2.2: Changed first sentence of second paragraph from "…defined in section 4.2.3" to "...defined in the last paragraph of section 4.2.3."

Table 1: Changed "TABLE 4.2-1" to "Table 1." Also changed in text where cited.

4.2.4, No. 5 on c_a, added English units of measure after the metric units.

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Revision (Continued)	A	01-20-2011	

4.2.4, Figure 1: Changed from "fHgap/ca" to "f H_{gap}/c_a" and "FIGURE 4.2.1" to "Figure 1" and where cited in text.

4.3.1.6, 2nd paragraph, 2nd sentence: Changed from "…frequency of less than 25 Hz" to "…frequency of less than 25 Hz to avoid ramp-up resonance."

4.3.2.6: Changed "must" to "shall."

4.3.4.2, 2nd sentence: Changed "are" to "shall be."

4.3.4.a(2): Changed from "+/-5%" to "±3 dB."
4.4.3, 2nd paragraph: Changed "Appendix A" to "Appendix B."

5: Moved to Appendix A, Guidance.

Appendix A: Changed "Appendix A" to "Appendix B."

A.2.1, 3rd paragraph: Added/revised in B.2.1, 3rd paragraph: "SEA has been used to solve a variety of aerospace problems. For many years, the most widely used and most thoroughly validated SEA program was the Vibroacoustic Payload Environmental Prediction System (VAPEPS). JPL operated the VAPEPS Management Center to maintain the code and provide user support to the aerospace community. In addition to its theoretical SEA predictions capability, VAPEPS also had the capability to make empirical predictions using flight and test databases. VAPEPS was used by most NASA Centers and most of the major aerospace contractors; however, it is no longer being maintained. Today, there are a number of commercial SEA codes available; among the most common are SEAM (Cambridge Collaborative, Inc.) and AutoSEA (ESI Group).

A.2.1, 4th paragraph: Deleted 4th paragraph in B.2.1 that read: "VAPEPS was originally developed by Lockheed Missile and Space Company under NASA GSFC funding. The Jet Propulsion Laboratory (JPL) 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 NASA Glenn Research Center."

<table>
<tr><th>Status</th><th>Document Revision</th><th>Approval Date</th><th>Description</th></tr>
<tr><td>Revision (Continued)</td><td>A</td><td>01-20-2011</td><td></td></tr>
<tr><td colspan="4">A.1.2, 5th paragraph: Added as 5th paragraph in B.1.2: “An effort by the Aerospace Corporation in California to integrate all test databases, analytical tools (including SEA, FEM, BEM), and scaling tools into one package, resulted in a package called Vibroacoustic Intelligent System Predicting Environments, Reliability, and Specifications (VISPERS). VISPERS is widely accepted by the Air Force.”

Changed “Appendix B” to “Appendix C.”</td></tr>
</table>

FOREWORD

This Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item.

This Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers.

This Standard establishes a uniform usage of test factors in the vibroacoustic verification process for spaceflight payload hardware.

Requests for information, corrections, or additions to this Standard should be submitted via "Feedback" in the Standards and Technical Assistance Resource Tool at http://standards.nasa.gov.

Original Signed By:	***01-20-2011***
Michael G. Ryschkewitsch NASA Chief Engineer	Approval Date

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PAYLOAD VIBROACOUSTIC TEST CRITERIA

1. SCOPE

The term “vibroacoustics” is defined as an environment induced by high-intensity acoustic noise associated with various segments of the flight profile. Vibroacoustics manifests itself throughout the payload in the form of transmitted acoustic excitation and as structure-borne random vibration. This Standard specifically addresses the acoustic and random vibration environments and test levels.

1.1 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. This Standard provides test factors for verification of payload hardware for qualification, protoflight, and flight acceptance programs. In addition, minimum workmanship test levels are included. With the exception of minimum workmanship test levels, these levels are provided in relation to the maximum expected flight level (MEFL). Although the major emphasis of this Standard is on test levels, the Standard also covers test duration, test control tolerances, data analysis, test tailoring, payload fill effects, and analysis methods.

This Standard defines procedures for developing vibroacoustic test criteria for NASA payloads. This document 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 of this Standard.

1.2 Applicability

This Standard recommends engineering practices for NASA programs and projects.

This Standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers and may be cited in contract, program, and other Agency documents as a technical requirement. This Standard may also apply to the Jet Propulsion Laboratory (JPL) or to other contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

Mandatory requirements are numbered and indicated by the word “shall.” Explanatory or guidance text is indicated in italics beginning in section 4.

This Standard applies only to spaceflight payload hardware. Launch vehicles, payloads launched by sounding rockets, aircraft and balloons, and ground support equipment (GSE) are excluded. This Standard does not apply to payload programs approved prior to the date of this document.

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 (refer to definitions in section 3.2). This Standard is applicable to the full range of payload hardware programs including prototype, protoflight, follow-on, spare, and reflight.

1.2.1 The levels and methods set forth herein shall form the basis for developing project-specific requirements for all new payload projects.

1.2.2 As much as possible, tailoring shall be identified early in the project's life cycle, e.g., prior to phase C/D implementation.

1.2.3 A permanent record shall be maintained by the project's quality assurance organization.

1.2.4 The Standard shall be applicable principally to Classes A, B, and C payloads.

Class D payloads may utilize tailoring as stated in section 4.3.6.

Classification of NASA payloads is defined in NPR 8705.4, Risk Classification for NASA Payloads.

1.2.5 Verification programs which meet or exceed the mandatory requirements for vibro-acoustic testing set forth in this document shall be considered compliant with this Standard.

1.3 Tailoring

Tailoring of this Standard for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the Technical Authority.

1.4 Summary of Verification Test Requirements

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

1.4.1 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 1.*

1.4.2 When the workmanship test level exceeds the qualification/protoflight and/or the flight acceptance levels, the test levels shall envelope the two spectra.

1.4.3 The minimum acoustic test level shall be 138 dB overall sound pressure level (OASPL). If the qualification/protoflight and/or flight acceptance test level is less than 138 dB OASPL, the spectrum shall be increased to this level.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this Standard as cited in the text.

2.1.1 The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 Non-use of specific versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at http://standards.nasa.gov or may be obtained directly from Standards Developing Organizations or other document distributors.

2.2 Government Documents

NASA

NASA-CR-173472	NASA Flight Electronics Environmental Stress Screening Survey, E.J. Marian, Washington, DC, December 1983
NASA-HDBK-7004	Force Limited Vibration Testing
NASA-HDBK-7005	Dynamic Environmental Criteria
NASA-STD-5002	Load Analyses of Spacecraft and Payloads
NASA-STD-7002	Payload Test Criteria
NASA-TN-2158	Statistical Techniques for Describing Localized Vibratory Environments of Rocket Vehicles, Robert E. Barrett
NPR 8705.4	Risk Classification for NASA Payloads (Revalidated July 9, 2009)

2.3 Non-Government Documents

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 (now Glenn 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
IEST-RP-DTE012.1	*Handbook for Dynamic Data Acquisition and Analysis*, Institute of Environmental Sciences and Technology, 2006
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
	Cassini Spacecraft Force Limited Vibration Test, K. Y. Chang

and Terry D. Scharton, Sound and Vibration Magazine, March 1998, pp. 16-20.

2.4 Order of Precedence

This Standard establishes requirements for uniform practices in the vibroacoustic verification process for spaceflight payload hardware but does not supersede nor waive established Agency requirements found in other documentation.

2.4.1 Conflicts between this Standard and other requirements documents shall be resolved by the responsible Technical Authority.

2.4.2 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. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

ASD	acceleration spectral density
BEA	boundary element analysis
C/D	countdown
c_a	speed of sound in air
CF	correction factor
DAF	direct acoustic field
dB	decibel
EMB	Engineering Management Board
EMC	Engineering Management Council
f	frequency
FEA	finite element analysis
g	acceleration due to gravity
GSE	ground support equipment
GSFC	Goddard Space Flight Center
H_{gap}	average gap distance
Hz	hertz
IES	Institute of Environmental Sciences
JPL	Jet Propulsion Laboratory
kg	kilogram
lb	pound
LeRC	Lewis Research Center (changed to Glenn Research Center)
MEFL	maximum expected flight level
NASA	National Aeronautics and Space Administration

NASTRAN	NASA Structural Analysis
OASPL	overall sound pressure level
µPa	micropascal
N	number of reflights
oct	octave
PSD	power spectral density
rms	root mean square
rss	root sum square
SEA	statistical energy analysis
SPL	sound pressure level
VAPEPS	Vibroacoustic Payload Environmental Prediction System
Vol	volume
Vol_{empty}	empty volume
$Vol_{payload}$	payload volume
Vol_{ratio}	volume ratio (of payload to empty fairing/cargo bay)
W	weight

3.2 Definitions

Acceptance Test: Test performed to demonstrate that the hardware is acceptable for flight. Also serves as a quality control screen to detect deficiencies in the flight build and is performed at levels and durations which reflect the expected flight environment. Also referred to as a flight acceptance test.

Component: A functional subdivision of a subsystem and is generally a self-contained combination of items performing a function necessary for the subsystem's operation.

Flight Acceptance Test: See Acceptance Test.

Follow-On Hardware: Flight hardware built in accordance with a design that has been qualified either as prototype or protoflight hardware. Follow-on hardware is subjected to acceptance testing.

Payload: An integrated assemblage of subsystems designed to perform a specified mission in space. Other terms that may be used to designate this level of assembly are Satellite, Spacecraft, or Observatory.

Protoflight Hardware: Hardware of a new design that is intended to fly. Protoflight hardware is subjected to protoflight testing.

Protoflight Test: Test performed on protoflight hardware that combines elements of qualification and acceptance testing. Protoflight testing exposes the hardware to qualification test levels for acceptance test durations.

Prototype Hardware: Hardware of a new design that is produced from the same drawings and using the same materials, tooling, manufacturing processes, inspection methods, and personnel competency levels as used for the flight hardware. Prototype hardware is dedicated test hardware that is not intended to fly. Prototype hardware is subjected to qualification testing.

Qualification Test: Test performed on prototype hardware that is intended to demonstrate that the test item will function within performance specifications after being exposed to levels which demonstrate margin over the expected flight environment. Durations for qualification testing are defined to demonstrate fatigue-life capability against planned ground testing and exposure to the flight environment.

Reflight Hardware: Flight hardware that has been used operationally in space and is to be reused in the same way. The verification program to which it is subject is dependent on previous environmental exposure, current status, and upcoming mission.

Spare Hardware: Flight hardware built in accordance with a design that is qualified by prototype or protoflight testing used to replace flight hardware that is no longer acceptable for flight. Spare hardware is subjected to acceptance testing.

Subsystem: A functional subdivision of a payload consisting of two or more components. For the purposes of this Standard an instrument (sensors and associated hardware) is considered a subsystem of the payload.

4. REQUIREMENTS

4.1 Methods and Assumptions Related to the 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 Qualification and Protoflight Tests

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

Protoflight tests are performed on flight and flight spare hardware where dedicated test hardware for qualification 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 qualification and flight acceptance tests. Protoflight tests are used to 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.

4.2.1.1 Acoustic qualification and protoflight tests shall be conducted at levels that envelope MEFL plus 3 dB and are equal to or greater than the minimum acoustic workmanship level defined in section 4.2.3.5.

4.2.1.2 Random vibration qualification and protoflight tests shall be conducted at levels that envelope the MEFL plus 3 dB and the minimum workmanship levels as defined in section 4.2.3.1.

Methods for determining the MEFL are described in section 4.4.

4.2.2 Acceptance Testing

Flight acceptance tests are performed on flight hardware. 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. Acceptance tests are performed for hardware that has been test qualified. Flight acceptance units include follow-on spacecraft hardware and flight spares that are identical in design and material configuration to the qualified article.

4.2.2.1 Acoustic flight acceptance tests shall be conducted at levels that envelope MEFL and are equal to or greater than the minimum acoustic workmanship level defined in section 4.2.3.5.

4.2.2.2 Random vibration flight acceptance tests shall be conducted at levels that envelope the MEFL and the minimum workmanship levels as defined in section 4.2.3.1.

Acceptance random vibration testing may be conducted at levels that are below MEFL, but no lower than the minimum workmanship levels as defined in Section 4.2.3, in cases where there is concern that exposing the hardware to additional testing at MEFL will pose a risk of fatigue damage. This includes testing of reflight/refurbished hardware which may experience multiple exposures to the test/flight environment. See Section 4.3.6 for test tailoring methods.

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.

4.2.3.1 For components weighing less than 50 kg (110 lb), the spectrum shown in table 1, Component Minimum Workmanship Random Vibration Test Levels, shall be used as a minimum vibration test specification.

This spectrum is within the envelope recommended in NASA CR-173472, NASA Flight Electronics Environmental Stress Screening Survey.

The minimum spectrum for a component whose mass exceeds 50 kg (110 lb) should be evaluated on an individual basis. A methodology for deriving a minimum workmanship vibration specification for components larger than 50 kg (110 lb) is given in Appendix B.1.3.

For very large components, vibration testing may not sufficiently excite internal hardware to adequately screen for workmanship defects. In such cases, a screening program should be initiated at lower levels of assembly. If testing is performed below the component level of assembly, the levels of table 1 may be used as a starting point. The susceptibility of the test *article to this vibration level must be evaluated and the test levels tailored so as not to induce unnecessary failures.*

If the test levels create conditions that exceed appropriate design safety margins or cause unrealistic modes of failure, the input spectrum may be notched below the minimum workmanship vibration levels shown in table 1. This can be accomplished when flight or test responses at a higher level of assembly are known or when appropriate force limits have been established.

4.2.3.2 The component shall be subjected to the random vibration test along each of three orthogonal axes for the appropriate duration as specified in section 4.3.3.

Table 1—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}

4.2.3.3 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 re-qualified in the hard-mounted configuration.

4.2.3.4 Workmanship acoustic testing shall be performed for all hardware levels of assembly described in section 4.3.1.

4.2.3.5 The minimum acoustic test level shall be 138 dB OASPL.

The minimum acoustic workmanship level of 138 dB OASPL may be achieved by uniformly scaling the test spectrum or by increasing the sound pressure level (SPL) in specific frequency bands.

Durations of testing are specified in section 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, Test Report for Acoustic and Structural Response Test, Test of Generic Spacecraft/Nose Fairing Configurations, and to NASA LeRC's Acoustic Fill Effect Test Program and Results, and predicted theoretically (refer to CC Report 93-11-12349-01, Acoustic Fill Factor Report, and CC Report 91-6-12104-1, Analysis and Evaluation of the Fill Factor).

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.*

4.2.4.1 The acoustic environment shall be adjusted to account for the fill effect of the payload within the launch vehicle fairing.

A methodology for calculating the payload fill effect is given in Appendix B.1.2.

4.2.4.2 The fill effect shall only be applied to payloads which exhibit extensive volumetric displacements.

4.2.4.3 If the payload is highly unsymmetrical or has discrete structures or appendages, then engineering judgment shall be utilized in applying the fill effect.

4.3 Test Methods and Specifications

4.3.1 Acoustic Tests

Acoustic tests are generally required at the payload level of assembly. However, acoustic testing is also required for any hardware which is considered susceptible to the acoustic environment. Aerospace hardware, which typically requires 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 acoustic impingement. In some cases, for example, large components or sub-assemblies, it may be necessary to perform acoustic and random vibration testing on hardware which is deemed susceptible to both direct acoustic impingement and mechanically transmitted random vibration.

The preferred method for performing acoustic testing is with a reverberant chamber test. Comparison of data from test articles subjected to both reverberant and current state-of-the art

DAF testing showed that the pressure field and measured responses from DAF testing can differ significantly from a reverberant field test even if the control microphones are kept within the test tolerances specified in Section 4.3.4.1. Because of the non-uniformity that may exist in the acoustic field generated by DAF testing, care must be taken when performing this type of test to have sufficient instrumentation on the test article to prevent exceeding hardware capability as the test level is increased and have an adequate number of microphones in place during the test to monitor the pressure field generated near critical items. It should also be noted that variability in the acoustic field generated by a DAF test may result in under-testing as well as over-testing in specific frequency bands and all efforts should be made to map the acoustic field relative to acoustically sensitive hardware to ensure that an adequate test can be achieved.

4.3.1.1 All hardware shall be assessed for sensitivity to the acoustic environment.

4.3.1.2 Acoustic testing shall be performed on all hardware that is considered susceptible to the acoustic environment.

4.3.1.3 Vibration isolators attenuate the high-frequency mechanical vibration below the level resulting from direct acoustic impingement; therefore, these components shall be reviewed as candidates for acoustic testing on a case-by-case basis. *A test program should be implemented that also satisfies the minimum workmanship criteria in section 4.2.3.*

4.3.1.4 Acoustic testing shall be performed by controlling the SPLs (dB re 20 μPa) in 1/3-octave bands over the specified frequency range.

4.3.1.5 All payload structures and components requiring acoustic testing shall be subjected to broadband reverberant field or direct acoustic field (DAF) testing.

4.3.1.6 The acoustical random noise source shall have an approximate normal amplitude distribution.

4.3.1.7 Sound pressure spectrum shall be computed over a period that provides SPLs within the test tolerances at lower frequencies.

4.3.1.8 Test levels shall be determined using the methods described in sections 4.2.1 and 4.2.2, and the test tolerances to be followed are described in section 4.3.4.

4.3.1.9 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.

4.3.1.10 The DAF test volume shall have sufficient dimensions to ensure that insertion of a test specimen will not affect the generation and maintenance of a broadband acoustic field above 50 Hz.

The following guidelines are recommended for DAF testing:

a. The minimum space between speakers and the test specimen should be no less than 1.5 meters.

b. The acoustical hot/cold locations within the test volume should be identified and minimized as much as practical over the frequency range of the test.

c. A minimum of eight microphones placed in critical locations of the testing volume should be used to control the SPLs.

d. The SPL levels from each control microphone should not deviate by more than 3 dB from the average.

The chamber and DAF testing volumes should 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 to avoid ramp-up resonance.

4.3.1.11 The microphones shall be positioned around the test chamber and DAF volume at sufficient distance from all surfaces to minimize 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.

4.3.1.12 In facilities where this distance cannot be achieved, the microphones shall be located in positions to be least affected by surface effects

4.3.1.13 The acoustic standing waves and structural modal coupling in reverberant field or DAF testing shall be assessed and steps taken to minimize the impact of such coupling on the health of the test specimen.

The following steps are recommended to address acoustic standing waves and structural modal coupling:

a. Identify empty chamber/DAF volume fundamental acoustic modes below a few hundred Hz.

b. Identify structural modes of the test article at low frequencies that may be susceptible to the acoustic standing pressure excitation.

c. Orient/position test hardware in the chamber/DAF volume to minimize acoustic modal coupling impact; i.e. stay away from pressure troughs/velocity peaks.

d. Instrument the chamber/DAF volume with additional microphones and place them *closer to sensitive components, if possible.*

e. Perform a low level acoustic test and thoroughly examine the structural/acoustic modal coupling at lower frequencies.

f. Re-orient test hardware in the chamber/DAF volume, if necessary, to minimize coupling effect; i.e. move sensitive components away from pressure nodes/velocity anti-nodes of the coupled frequencies.

g. Examine low level data (both sound pressure and acceleration/strain responses) by extrapolating to the full 0 dB acoustic level and proceed if no structural issues are anticipated due to coupling.

h. For large test hardware, where re-orientation may not be possible, use additional instrumentation to better gauge the coupling issue.

4.3.1.14 The number and location of control microphones averaged to determine the applied sound field shall be determined based on the size, configuration, and number of large surfaces of the test specimen.

For most payloads and spacecraft, a minimum of four control microphones are recommended for reverberant acoustic testing Minimum number of control microphones recommended for DAF testing are specified in 4.3.1.10. In some cases it may be necessary to add microphones to adequately measure the sound field in the proximity of each major surface of the test specimen.

4.3.1.15 With the specimen in the test chamber or DAF volume, the acoustic spectrum shall be shaped at a level which is no greater than -6 dB of the full level specification.

4.3.1.16 The time required to shape the spectrum shall be minimized to avoid possible fatigue of the test specimen.

As an alternative to shaping the spectrum at lower excitation levels with the specimen in the test chamber or DAF volume, a dummy specimen may be positioned in the test chamber or DAF volume and the spectrum shaped at the test level. The first run with the actual test hardware should still be performed at a level that is no greater than -6dB of the full level specification.

4.3.2 Random Vibration Tests

Random vibration testing is generally required for electrical, electronic, and electromechanical components and mechanisms. Random vibration testing is also required for any hardware whose responses are driven by the mechanically transmitted random vibration due to the vibro-acoustic environment. 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.*

Random vibration testing, which accounts for the low-frequency mechanically transmitted launch environment below 100 Hz, may be considered as an alternative to the system level sine vibration test requirements of NASA-STD-7002 (refer to "Cassini Spacecraft Force Limited Vibration Test").

4.3.2.1 All hardware shall be assessed for susceptibility to mechanically transmitted random vibration due to the vibroacoustic environment.

4.3.2.2 Random vibration testing shall be performed on all hardware that is considered susceptible to mechanically transmitted random vibration due to the vibroacoustic environment.

4.3.2.3 Compact payloads weighing less than 450 kg (1000 lb) shall be subjected to system-level random vibration testing unless an analysis and/or heritage data show that the payload responses are clearly dominated by the direct acoustic environment.

4.3.2.4 The test specimen shall be subjected to random vibration with a Gaussian amplitude distribution in each of three orthogonal axes.

4.3.2.5 Random vibration testing shall be performed by controlling the acceleration spectral density (g^2/Hz) in 25 Hz or less frequency bandwidths over the frequency range from 20 to 2000 Hz.

4.3.2.6 The spectrum shall be within the test tolerance specified in section 4.3.4.

4.3.2.7 The control accelerometer(s) shall be mounted on the test fixture near the attachment points.

4.3.2.8 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 control scheme shall be consistent with the test requirement derivation.

4.3.2.9 The test fixture shall be subjected to a bare resonance survey up to 2000 Hz prior to the start of testing.

4.3.2.10 If practical, the fixture shall have no resonances within the test frequency range.

4.3.2.11 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 that 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 over-tests 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 over-testing 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 NASA-HDBK-7004, Force Limited Vibration Testing.

4.3.3 Test Duration

The durations for the tests described in sections 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) The vibroacoustic qualification test durations shall be 2 minutes for the acoustic test and 2 minutes in each of the 3 orthogonal axes for the vibration test.

(2) If the flight hardware is to be reflown N times, the corresponding qualification test durations shall be 2 + 0.5N minutes.

b. Protoflight Test Duration

The vibroacoustic protoflight test durations shall be 1 minute for an acoustic test and 1 minute in each of the 3 orthogonal axes for a vibration test.

c. Acceptance Test Duration

The vibroacoustic acceptance test durations shall be 1 minute for an acoustic test and 1 minute in each of the 3 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 section 4.3.6).

4.3.4 Test Control Tolerances

4.3.4.1 The acceptable tolerances for vibroacoustic testing shall be as follows:

a. Vibration

(1) Composite rms acceleration .... ±10%
(2) Acceleration spectral density (25 Hz or less frequency bandwidth resolution) .... ±3 dB
(3) Frequency... ±5%
(4) Test duration ....+10%, -0%

b. Acoustic
(1) Individual 1/3-octave band SPLs (50 to 3000 Hz) ....±3 dB
(2) Overall SPL...±1 dB
(3) Test duration.. +10%, -0%
(4) Facility capability will determine SPL tolerances below 50 Hz and above 3000 Hz.

The above test tolerances do not preclude the acceptance level from exceeding the qualification/protoflight level in a given frequency band. If this is identified as a risk for the flight hardware, then tighter test tolerances should be implemented for both qualification/protoflight tests (+3/-1.5 dB) and for acceptance tests (+1.5/-3dB) to prevent this occurrence.

4.3.5 Test Configuration

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.

(1) The electrical operating mode shall be in accordance with the test plan.
(2) 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 pre-launch pressure.

d. *For extremely large payloads, performance of a random vibration test at the payload level of assembly may be impracticable (because of test facility limitations).* In that case, testing at the subsystem level of assembly shall be assessed.
For extremely large components, random vibration tests may need to be supplemented or replaced by an acoustic test due to test facility limitations.

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

If the planned random vibration tests are not capable of inducing sufficient excitation to internal electric, electronic, and electromechanical devices to meet the workmanship requirements defined in section 4.2.3, workmanship testing should be conducted at lower levels of assembly (e.g., down to the board level, if necessary).

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.

4.3.6.1 Nevertheless, all requirements of the Standard shall be evaluated for each spacecraft application.

4.3.6.2 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, e.g., 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.*

4.3.6.3 The logic used to develop a specific notching rationale shall be validated.

Notching can be in the form of "force limiting" as discussed in section 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

Preferred methods for dynamic data acquisition and analysis of vibroacoustic data are included in NASA-HDBK-7005, Dynamic Environmental Criteria.

4.4.1 This document shall be used as a guideline for vibroacoustics data acquisition and analysis.

4.4.2 In practice, the maximum expected environment shall be based on one or more of the following:

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 included and properly scaled.

4.4.3 The minimum statistical basis to be used for defining MEFL shall be P95/50 assuming a log-normal distribution of the data. The P95/50 level is defined as enveloping 95 percent of the data with a 50 percent confidence level.

The methodology for calculating the P95/50 level based on measured flight data is described in Appendix B1.1.

If less than three data samples are available, then the P95/50 level may be calculated based on the methods presented in Appendix B.1.1 using the assumptions of a large sample size with a log-normal distribution and a standard deviation of 3 dB. These assumptions are based on data presented in NASA-HDBK-7005 for repeated measurements taken at a common location on the same launch vehicle for over 40 flights. Under these assumptions, the single-tailed tolerance factor K is equal to 1.65 and the P95/50 normal tolerance limit is given by $P95/50 = X_m + KS_x = X_m + 1.65*3dB = X_m + 5dB$

Where

X_m = *Log-normal mean of the data. If only one data point is available, then this data point is assumed to be the mean level.*

K = Single-tailed tolerance factor. Equal to 1.65 for a large data sample.

S_x = *Standard deviation. Assumed to be 3 dB when less than three data points exist.*

4.4.4 The maximum bandwidths to be used for deriving the enveloped MEFL spectrum shall be as defined below:

Acoustic SPL: 1/3 octave bands

Random PSD: 1/6 octave bands.

4.4.5 Random vibration levels derived using vibroacoustic prediction techniques, such as SEA and boundary element analysis (BEA), shall meet the bandwidth requirements of 4.4.4 and the analysis results be scaled to account for the peak response of the hardware.

SEA results are typically calculated as 1/3 octave band data and represent a spatially averaged response. It is recommended that 6 dB be added to SEA results to account for these effects when deriving the random vibration environment.

Methods for vibroacoustic analysis are discussed in more detail in Appendix B.

4.4.6 Ground test operations and transportation vibroacoustic levels shall be controlled so that levels produced by these events do not exceed the MEFLs.

4.4.7 If it is not practicable to constrain the ground test and/or transportation environments, the environments shall be considered as contributing to the design and test criteria.

APPENDIX A

GUIDANCE

A.1 Key Word Listing

Acceptance test
Acoustic
Qualification test
Random vibration
Vibration
Vibroacoustic

A.2 Background

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 GSE. These efforts resulted from a recommendation of the NASA Engineering Management Council (EMC), currently called the Engineering Management Board (EMB), 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 multi-Center projects mandates that qualification and acceptance test practices be consistent across the Agency. 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 help to streamline the inter-Center 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. 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 standard’s 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 contained a resolution of the divergent issues and the necessary core information to develop this Standard.

In 2009, the NASA Safety and Engineering Center was tasked to work with representatives from the various NASA Centers to develop a version of this Standard which could be applied as a mandatory standard across all NASA flight programs. As a result of these discussions, the Standard was revised to identify the minimum set of mandatory requirements for vibroacoustic testing that will ensure that the hardware will survive and perform as expected when exposed to the flight environment. In addition, the guidance in the document was expanded to cover standard practices across the Agency and reflect the state of the art in terms of vibroacoustic analysis and test techniques.

APPENDIX B

METHODS FOR VIBROACOUSTIC ANALYSES

B.1 Data Analysis

B.1.1 Statistical Standards

The vibroacoustic test levels are a function of the MEFL, as specified in sections 4.2.1 and 4.2.2, and are based upon statistically estimated spectral levels. A $P_{95/50}$ level is recommended 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

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

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 μPa^2 within a defined bandwidth and X is the spectral value in decibels referenced to 1 g^2/Hz or 1 μPa^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 dBs, which means that 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. (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):

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

For random vibration data, it may be preferable not to treat the data in dB form. Thus, the population could be defined without a factor of 10 or consideration of a reference value: $x = \log_{10} y$. 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 dBs, would become equal to 10 CF $(K S_x)$ and the following modified expression would result:

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

In this case, the statistical terms $X_{95/50}$*,* $\bar{X}$*, and* S_x *are computed for a population defined as* $x = log_{10y}$*.*

Even though a log normal distribution or modified form 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-D-2158, Statistical Techniques for Describing Localized Vibratory Environments of Rocket Vehicles).

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.*

B.1.2 Fill Effects

The following methodology may be used to adjust the acoustic spectrum to account for payload fill effects:

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).*

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

where:

c_a is the speed of sound in air (typically 344.4 meters/second (1130 feet/second)).

f is the 1/3-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. Determine the acoustic levels for the empty fairing/cargo bay. In many cases the acoustic spectrum provided for a specific launch vehicle includes a baseline fill factor. If applicable, subtract any baseline fill factor from the acoustic spectrum to derive the acoustic levels for the empty fairing/cargo bay volume.

7. 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).

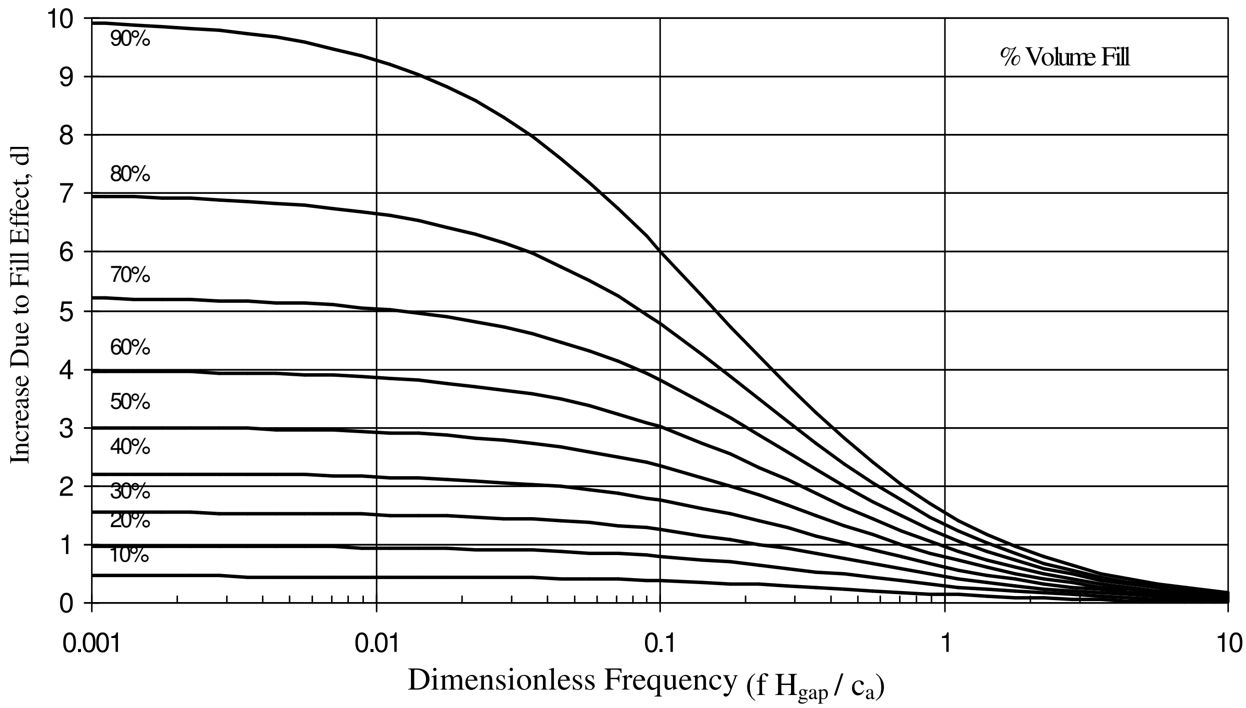

Figure 1—Fill Factor Design Chart

Figure 1 is a design chart that illustrates the fill effect obtained from the fill effect equation versus a dimensionless frequency ($f\,H_{gap}/c_a$), for various Vol_{ratio}. The percent volume fill shown in figure 1 is relative to the empty fairing/cargo bay volume, and the increase due to the fill effect should be applied to the acoustic level for the empty fairing/cargo bay with any baseline fill effects removed.

Fill effects greater than those predicted are possible in individual 1/3-octave bands at low frequencies. These exceedances are due to unique payload geometries that 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 (FEA) may be warranted.

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.

B.1.3 Mass Attenuation of the Minimum Workmanship Vibration Level

The plateau acceleration spectral density level (ASD) may be reduced for components weighing between 50 and 200 kg (110 and 440 lb) according to the component weight (W) up to a maximum of 6 dB as follows:

	Weight in kg	Weight in lb
dB reduction	= 10 log(W/50)	10 log(W/110)
ASD (plateau) level	= 0.04•(50/W)	0.04•(110/W)

The sloped portions of the spectrum are maintained at plus and minus 3 dB/oct. Therefore, the lower and upper break points, or frequencies, at the ends of the plateau become:

FL = 80 (50/W) [kg] FL = frequency break point low end of plateau
= 80 (110/W) [lb]

FH = 500 (W/50) [kg] FH = frequency break point high end of plateau
= 500 (W/110) [lb]

The test spectrum should not go below 0.01 g^2/Hz. For components whose weight is greater than 200-kg or 440 pounds, the workmanship test spectrum is 0.01 g^2/Hz from 20 to 2000 Hz with an overall level of 4.4 g_{rms}. The mass-attenuated workmanship spectrum is shown in figure 2.

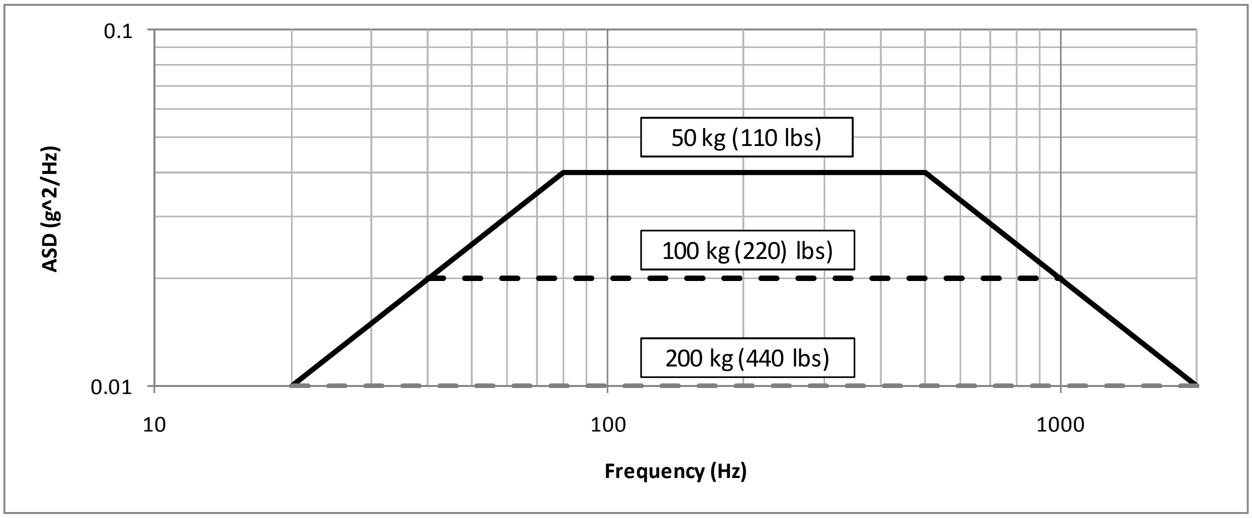

Figure 2—Mass Attenuated Workmanship Vibration Spectrum

B.2 Analysis Methods

B.2.1 SEA

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-D-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 for predicting vibroacoustic response of structures, such as scaling, FEA, BEA, and hybrid methods which combine FEA and SEA techniques. SEA covers the medium- to high-frequency range (typically several hundred Hz and higher). Although scaling techniques may be accurate in the mid- to high-frequency range, a database of similar structure is not always available. SEA allows new structure designs to be evaluated. Additionally, SEA modeling does not require the detailed structural modeling that FEA, BEA, and hybrid do; therefore, SEA is both less expensive and quicker to perform than the other methods and easily allows for parameter redesign analysis. However, the SEA method does a poor job of predicting vibroacoustic response in frequency ranges in which the structure has few modes within the bandwidth of interest. Therefore, most SEA results are not accurate in the mid- to low-frequency range. In addition, SEA provides results that represent the spatially averaged spectral response of the structure. If localized response quantities (acceleration, force, or stress) are desired, these must be estimated from the SEA results or may require that alternate analysis methods to be used.

SEA has been used to solve a variety of aerospace problems. For many years, the most widely used and most thoroughly validated SEA program was the Vibroacoustic Payload Environmental Prediction System (VAPEPS). However, JPL has stopped maintaining the VAPEPS code and providing user support to the aerospace community. Today, there are a number of commercial SEA codes available; among the most common are SEAM (Cambridge Collaborative, Inc.) and VA-One (ESI Group).

B.2.2 FEA

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. Aircraft companies did significant early work in this field in the 1950s and 1960s; and the first widely used FEA program, NASA Structural Analysis (NASTRAN), was originally developed by NASA for the NASA/contractor community. There are a variety of commercially available FEA programs in addition to NASTRAN (e.g., among the most common are ANSYS, ABAQUS, STARDYNE, ALGOR, and COSMOS).

Vibroacoustic analysis has remained mostly 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 (section B.2.1), BEA (section B.2.3), and Hybrid techniques are often used to predict the structural vibroacoustic response. Although the SEA methodology is powerful, at lower frequencies (typically below a few hundred Hz), SEA's underlying assumptions regarding modal density result in predictions that are invalid. But FEA, BEA, and Hybrid techniques provide alternative methodologies for making vibroacoustic predictions in this frequency range.

Two different types of FEA methods exist for predicting acoustic response. The acoustic FEA approach models both the structure and the acoustic fluid (typically air) with finite elements to simulate how the system responds to vibroacoustic input. This method provides accurate predictions but developing the models for this type of analysis is very cumbersome and requires very fine mesh sizes to accurately represent the structure-fluid interaction. The acoustic FEM modeling technique is primarily used for interior noise studies, modal analysis, and damping treatments. Traditional FEA can be used to predict vibroacoustic response by applying random pressure fields to the surfaces of the model. This approach, also called the "Patch Method," has the advantage that existing structural models can be used. However, the patch method requires assumptions about the correlation of the pressure load over a given surface as a function of frequency and cannot easily replicate physical behaviors, such as near field effects, edge effects, and double-sided pressure loading on exposed surfaces. These effects are usually accounted for by frequency-dependent scaling factors which are applied to the input and response results. Care must be taken in defining the appropriate scaling factors or else the patch method may significantly over- or under-predict acoustic response. Typically the patch method tends to be conservative below approximately 200 Hz but requires validation against test data from similar structures to provide useful results in higher frequency ranges.

B.2.3 BEA

BEA is a deterministic approach and is able to predict the acoustic-induced structural vibration in frequency domain, the sound fields in open and closed spaces, and sound field radiated by vibrating structures. The BEA method models the structure with finite elements discussed in section B.2.2 but uses boundary elements to model the fluid. The accuracy of the predicted results depends upon the fidelity of the finite element model.

In section B.2.1, the SEA vibroacoustic modeling technique was discussed in some detail. SEA is applicable to the frequency range of structures that have adequate modal densities. The BEA method that couples the structure (finite element) and fluid (boundary element) is a method applicable to the low- to mid-frequency range. Several commercial BEA codes have emerged in the last decade or so. The codes most commonly used by the aerospace community are SYSNOISE and VA-One. Unlike the finite element based acoustic methods which require very large models to get accurate results, the meshing requirements for the boundary element method are greatly simplified.

B.2.4 Complete Analytical Tools

The analyst may need to combine different methods of analysis discussed in sections B2.1—B.2.3 to obtain a complete vibroacoustic solution for structures impacted by acoustic pressures. In the mid-frequency range, new hybrid methods are emerging that combine SEA with FEA.

However, the development of the new hybrid methods is in their infancy and awaits verification using experimental data. In general, BEA and acoustic FEA techniques are applicable to the low- to mid-frequency range, the hybrid SEA/FEA methods are applicable to the mid-frequency range, and SEA to the high-frequency region. As mentioned in section B.2.2, the patch method can also be used to derive structural response predictions in the low-frequency range using standard FEA techniques, but care must be taken when using this approach to account for physical effects not represented by the analysis so as to prevent significant over- or under-prediction of response.

APPENDIX C

VIBROACOUSTIC LOAD PREDICTIONS

C.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 dependent on the launch vehicle and payload. Analysis techniques simulating the induced levels are used to predict the resulting loads. More detailed information is included in NASA-STD-5002, Load Analyses of Spacecraft and Payloads.

C.1.1 Combination of Loads

The following is an excerpt from NASA-STD-5002:

> *...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.