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Office of the NASA Chief Engineer

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NOT MEASUREMENT SENSITIVE

PAYLOAD VIBROACOUSTIC TEST CRITERIA

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DOCUMENT HISTORY LOG

Status	Document Revision	Change Number	Approval Date	Description
Baseline			06-21-1996	Initial Release
Revision	A		01-20-2011	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." 4.2.4, No. 5 on c_a, added English units of measure after the metric units. Table 1: Changed "TABLE 4.2-1" to "Table 1." Also changed in text where cited. 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

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				4.2.4, No. 5 on c_a, added English units of measure after the metric units. 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.”
Revision	B		2017-11-07	Significant changes were made to this NASA Technical Standard. It is recommended that it be reviewed in its entirety before implementation. Key changes were: Moved requirements statements previously found in the scope section to the requirements section. Removed shall statement from two requirements and made them statements of fact. Updated various sections within the document for clarification. Applicable documents were updated where necessary (i.e., new revisions or change of authors). Direct field acoustic testing methods have been expanded in certain sections. Finite element analysis methodologies have been expanded in Appendix B.2.2. To facilitate requirements selection and verification by NASA programs and projects, a Requirements Compliance Matrix is provided in Appendix D.
Revision	C		2026-07-14	Significant changes were made to this NASA Technical Standard. It is recommended that it be reviewed in its entirety before implementation. Key changes were: removed shall language

				on requirements 1-7 in section 1 due to requirements needing to be in section 4, rewording of several payload vibroacoustic requirements mainly for clarification, expansion of control accelerometers requirement for further clarification. Significant additions made to Appendix C for further clarification and guidance on vibroacoustic modeling. New references have been added. Technical edits made: reformatted to comply with the NASA-STD template approved on 11-17-2022. - Reordered appendices - Updated language in the forward, section 1, and section 2 to comply with the template. - Updated title page and TOC - Updated table order and added a title to the table in section 4.1

FOREWORD

This NASA Technical Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods 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; applicable technical requirements may be cited in contract, program, and other Agency documents. This language applies to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center), other contractors, recipients of grants, cooperative agreements, or other agreements only to the extent specified or referenced in the applicable contracts, grants, or agreements.

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

Submit requests for information via "Email Feedback" at https://standards.nasa.gov

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NASA Technical Standards Program Executive
On Behalf of:

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Katherine Van Hooser	July 14th, 2026
NASA Deputy Chief Engineer	Approval Date

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PAYLOAD VIBROACOUSTIC TEST CRITERIA

1. SCOPE

The term "vibroacoustics", in this Standard, is referred to as an environment induced by high-intensity acoustic noise associated with various segments of the flight profile. The term "payload", in this Standard, is not limited to uncrewed systems such as satellites but also includes crewed systems such as Orion. 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 for spaceflight payloads. 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. This Standard is applicable principally to Classes A, B, and C payloads.

1.1. Purpose

This Standard establishes the uniform use 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, it 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 Standard 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

1.2.1. Programs and Projects

This Standard recommends engineering practices for NASA programs and projects. The levels and methods set forth herein form the basis for developing project-specific requirements for all new payload projects.

Classification of NASA payloads is defined in NPR 8705.4, Risk Classification for NASA Payloads.
For Class D payloads, NASA-STD-7001 is a guidance document. Class D payloads may utilize tailoring as stated in section <u>4.4.6 Test Tailoring Methods</u> in this Standard.

The levels of assembly for which this 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 Definitions). This Standard is applicable to the full range of payload hardware programs, including prototype, protoflight, follow-on, spare, and reflight.

Some discussion of analytical methods used as an aid to develop requirements is presented in APPENDIX C: METHODS FOR VIBROACOUSTIC ANALYSES. The applicability and limitations of the methods are discussed. A brief description of vibroacoustic loads is described in APPENDIX D: VIBROACOUSTIC LOAD PREDICTIONS; for more detail, see NASA-STD-5002, Load Analyses of Spacecraft and Payloads.

Verification programs which meet or exceed the mandatory requirements for vibroacoustic testing set forth in this Standard are considered compliant with this Standard.

1.2.2. Approved Centers for Use

This Standard is approved for use by NASA Headquarters and NASA Centers and Facilities, and applicable technical requirements may be cited in contract, program, and other Agency documents. This language applies to the Jet Propulsion Laboratory (a Federally Funded Research and Development Center), other contractors, recipients of grants, cooperative agreements, or other agreements only to the extent specified or referenced in the applicable contracts, grants, or agreements.

1.2.3. Revision Reference

References to "this Standard" refer to NASA-STD-7001; references to other documents state the specific document information.

1.2.4. Requirements Numbering

Verifiable requirement statements are designated by PVTR (Payload Vibroacoustic Test Requirement), numbered, and indicated by the word "shall." This Standard contains 64 requirements. To facilitate requirements selection by NASA programs and projects, a Requirements Identification Matrix is provided in APPENDIX A: REQUIREMENTS IDENTIFICATION MATRIX.

1.2.5. Guidance Text

Explanatory or guidance text is indicated in italics beginning in Section 4, REQUIREMENTS. The terms "may" or "can" denote discretionary privilege or permission, "should" denotes a good practice and is recommended but not required, "will" denotes expected outcome, and "is/are" denotes descriptive material or a statement of fact.

1.3. Tailoring

1.3.1 Tailoring of the requirements in this Standard for application to a specific program or project is acceptable when formally approved by the delegated NASA Technical Authority (such as the Engineering TA for technical requirements) in accordance with NPR 7120.5, *NASA Space Flight Program and Project Management Requirements*, and documented in program and project requirements. The delegated NASA TA is identified in the program or project governance structure and is accountable for ensuring that any tailored requirements maintain compliance with applicable agency policies.

Note: The appropriate TA for tailoring depends on the nature of the requirement being modified. Technical Authorities are independent from program/project management and provide authoritative oversight in their respective domains.
Primary TA roles are:

- *Engineering Technical Authority (ETA) - Responsible for technical requirements, design, and verification.*

- *Safety and Mission Assurance Technical Authority (S&MA TA) - Responsible for safety, reliability, and quality assurance requirements.*

- *Health and Medical Technical Authority (HMTA) - Responsible for crew health and medical requirements (for human spaceflight programs).*

1.3.2 As much as possible, identify tailoring early in the project's life cycle, e.g., during the preliminary design phase.

2. APPLICABLE DOCUMENTS

2.1. General

2.1.1 Documents listed in this section contain provisions constituting requirements of this Standard as cited in the text. Latest issuances of cited documents apply unless specific versions are designated. Obtain approval from the delegated NASA Technical Authority to use a version other than as designated.

2.1.2 Access applicable documents at https://standards.nasa.gov or obtain documents directly from the Standards Developing Body, other document distributors, information provided or linked, or by contacting the office of primary responsibility for this Standard.

Note: References are provided in APPENDIX B: REFERENCES AND BACKGROUND.

2.2. Government Documents

NASA

NPR 7120.5, NASA Space Flight Program and Project Management Requirements

2.3. Non-Government Documents

None.

2.4. Order of Precedence

2.4.1 The requirements and standard practices established in this Standard do not supersede or waive existing requirements and standard practices found in other Agency documentation.

2.4.2 Conflicts between this Standard and other requirements documents will be resolved by the delegated Technical Authority.

2.4.3 This Standard does not address safety considerations that are covered thoroughly in other documents; but if a conflict arises, safety always takes precedence. Nothing in this Standard, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. ACRONYMS, ABBREVIATIONS, SYMBOLS, & DEFINITIONS

3.1. Acronyms, Abbreviations, and Symbols

%	percent
μPa	micropascal
ASD	acceleration spectral density
BEA	boundary element analysis
BEM	boundary element method
C/D	countdown
c_a	speed of sound in air
CF	correction factor
dB	decibel
EMB	Engineering Management Board
EMC	Engineering Management Council
f	frequency
FE	finite element
FEA	finite element analysis
FEM	finite element model
FL	frequency breakpoint low
FH	frequency breakpoint high
g	acceleration due to gravity
grms	root mean square acceleration in units of g
GSE	ground support equipment
GSFC	Goddard Space Flight Center
H_{gap}	average gap distance (payload-to-fairing)

Hz	hertz
IEST	Institute of Environmental Sciences and Technology
K	normal tolerance factor
kg	kilogram
lb	pound
LeRC	Lewis Research Center (renamed Glenn Research Center)
LSP	launch service provider
MDOF	multi-degree of freedom
MEFL	maximum expected flight level
MPC	multi-point constraint
MSFC	Marshall Space Flight Center
N	number of reflights
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis
NPR	NASA Procedural Requirements
OASPL	overall sound pressure level
oct	octave
Pa	pascal
PSD	power spectral density
PVTR	Payload Vibroacoustic Test Requirement
rms	root mean square
RSS	root sum square
SEA	statistical energy analysis
SI	Système Internationale or metric system of measurement
SPL	sound pressure level
STD	standard
S_x	sample standard deviation
Vol	volume
Vol_{empty}	empty volume
$Vol_{payload}$	payload volume
Vol_{ratio}	volume ratio (of payload to empty fairing/ enclosure)
W	weight
$\overline{X}$	sample average

3.2. Definitions

Acceptance Test: An acceptance test, also referred to as a flight acceptance test, is a test performed to demonstrate that the hardware is acceptable for flight. Acceptance tests are performed for hardware that has been test qualified and are conducted to demonstrate satisfactory performance of flight systems relative to the expected environment and to reveal inadequacies in workmanship and material integrity. Flight acceptance units include follow-on spacecraft hardware and flight spares that are identical in design and material configuration to the qualified article.

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 flight and flight spare hardware that combines elements of qualification and acceptance testing. The protoflight testing of flight spares would occur only when the first item built is declared to be a spare. Protoflight testing exposes the hardware to qualification test levels for acceptance test durations. 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, but they do not test for the full service life or provide qualification margin against fatigue life capability. Protoflight testing is markedly differentiated from qualification testing.

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. Qualification testing is conducted to verify that hardware and systems design, materials, and manufacturing processes have produced equipment that conforms to development specification requirements.

Reflight Hardware: Flight hardware that has been used operationally in space and is to be reused in the same way (i.e. form, fit, function, and enveloping environment remain unchanged from flight-to-flight). The verification program to which it is subject is dependent on previous environmental exposure, current status, and upcoming mission. Any deviations in how the flight hardware is to be reused should be thoroughly addressed.

Service Life: The service life of an item starts at the completion of fabrication and continues through all acceptance/protoflight testing, handling, storage, transportation, prelaunch testing, all phases of launch, orbital operations, disposal, reentry, or recovery from orbit, refurbishment, retesting, and reuse that may be required or specified.

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. Summary of Verification Test Requirements

Table 1—Summary of Verification Test Requirement Levels and Durations

Maximum Expected Flight Level (MEFL)	95%/50% Probability/Confidence Level (P95/C50)
Minimum Test Levels	
Qualification	Flight Acceptance +3 dB
Protoflight	Envelope of MEFL +3 dB and Minimum Workmanship
Flight acceptance	Envelope of MEFL and Minimum Workmanship
Minimum component vibration workmanship test	6.8 grms
Minimum acoustic workmanship test	138 dB OASPL (ref: 20 micropascals)
Minimum 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

4.1.1. **[PVTR 1]** A permanent record of all payloads and environments generated using this Standard **shall** be maintained by the project's quality assurance organization.

4.2. Methods and Assumptions Related to the Use of Verification Tests

4.2.1. Purpose of Tests and Test Factors

The purpose of testing with test factors is to prove design performance at the maximum expected flight level (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.

4.3. Test Levels

4.3.1. Qualification and Protoflight Tests

4.3.1.1. **[PVTR 2]** Acoustic qualification tests **shall** be conducted at levels that envelope flight acceptance levels plus 3 dB.

4.3.1.2. **[PVTR 3]** Acoustic protoflight tests **shall** be conducted at levels that envelope MEFL plus 3 dB and minimum workmanship levels defined in section 4.3.3.

[Rationale: Minimum workmanship test levels may exceed MEFL plus 3 dB or MEFL.]

4.3.1.3. **[PVTR 4]** Random vibration qualification tests **shall** be conducted at levels that envelope flight acceptance levels plus 3 dB.

4.3.1.4. **[PVTR 5]** Random vibration protoflight tests **shall** be conducted at levels that envelope MEFL plus 3 dB and minimum workmanship levels defined in section 4.3.3.

[Rationale: Minimum workmanship test levels may exceed MEFL plus 3 dB or MEFL.]

Methods for determining the MEFL are described in section 4.5.

4.3.2. Acceptance Testing

4.3.2.1. **[PVTR 6]** Acoustic flight acceptance tests **shall** be conducted at levels that envelope

MEFL and are equal to or greater than the minimum acoustic workmanship levels defined in section 4.3.3.

4.3.2.2. **[PVTR 7]** Random vibration flight acceptance tests **shall** be conducted at levels that envelope the MEFL and the minimum workmanship levels as defined in section 4.3.3.

This includes testing of reflight/refurbished hardware which may experience multiple exposures to the test/flight environment. See section 4.4.6 for Test Tailoring Methods.

4.3.3. Workmanship

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

4.3.3.1. **[PVTR 8]** For components weighing less than 50 kg (110 lb), the spectrum shown in Table 2, Component Minimum Workmanship Random Vibration Test Levels, **shall** be used as a minimum vibration test specification.

Table 2—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 grms

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 C.1.3 Mass Attenuation of the Minimum Workmanship Vibration Level.

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 2 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 2. 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.

4.3.3.2. **[PVTR 9]** The component **shall** be subjected to the minimum workmanship random vibration test level along each of three orthogonal axes for the appropriate duration as specified in section 4.4.3.

For hardware that has successfully passed protoflight or acceptance testing and undergoes subsequent rework, consideration may be given to performing less than three axes of vibration for minimum workmanship testing post-rework. This decision should be based on assessment of input necessary to screen the repair.

4.3.3.3. **[PVTR 10]** Components **shall** be hard-mounted to the shaker.

[Rationale: For components mounted on isolators, in foam stowage, or highly compliant mounting hardware, adequate workmanship testing may not be achieved in the flight configuration. Hard-mounting to the shaker, without isolation, ensures the component is fully exposed to workmanship levels.]

4.3.3.4. **[PVTR 11]** Workmanship acoustic testing **shall** be performed for all hardware levels of assembly described in section 4.4.1.

4.3.3.5. **[PVTR 12]** The minimum workmanship acoustic test level **shall** be 138 dB overall sound pressure level (OASPL), via one of the following methods:

Method 1: The minimum acoustic workmanship level is specified in Table 8.11 of NASA-HDBK-7005, Dynamic Environmental Criteria.

Method 2: The minimum acoustic workmanship level of 138 dB OASPL may alternatively be achieved by uniformly scaling the MEFL spectrum.

[Rationale: 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. The purpose is to provide enough broadband energy to reveal workmanship and material flaws for acoustically responsive hardware. A goal should be set to produce a random response of adequate level to expose faulty integration. Achieving 0.04 g^2/Hz at some resonances in the bands from 150-500 Hz is a reasonable target.]

Durations of testing are specified in section 4.4.3.

4.3.4. Acoustic Fill Effect

Understanding of the acoustic fill effects for specifying an acoustic environment is important for *payload hardware design and testing. The fill effect describes how internal SPLs change between an empty payload fairing and a fairing with a payload mounted inside. This also applies more generally to any encapsulated payload that may be enclosed by structures that are unlike a typical payload fairing launch vehicle accommodation. The fill effect is an increase in internal SPL, relative to that of an empty fairing, due to the payload mounted inside the fairing. This change in SPL 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-TM-106688, 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 payloads within a given payload volume.*

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

4.3.4.1. **[PVTR 13]** For payloads which exhibit extensive volumetric physical fill, 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 factor-is given in Appendix C.1.2 Fill Effects. *This method is suggested as a tool to guide conceptual studies through preliminary design. For final design and implementation, detailed vibroacoustic modeling, such as the use of acoustic finite elements, should supersede use of the fill factor. It is possible fill factor can result in severe underestimation of the acoustic environment at lower frequencies.*

Generally, payload volume ratios less than 50% are considered to have negligible fill effect, thus such effects can be disregarded in estimation of payload acoustics (this lower threshold should be coordinated with the launch service provider [LSP]). The launch vehicle user guide should be consulted to find if the provided fairing internal environment is for an empty fairing or had assumed a particular fill effect.

4.3.4.2. **[PVTR 14]** If the payload is highly unsymmetrical or has discrete structures or appendages, then engineering judgment **shall** be utilized in applying the fill effect.

[Rationale: Because of the unique acoustic modes of each payload and fairing/enclosure combination, caution should be used when interpreting flight data fill effects and applying them to another payload and fairing/enclosure combination which is geometrically dissimilar.]

4.4. Test Methods and Specifications

4.4.1. 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 large area-to-weight ratio structures such as skin panels, reflectors, dish antennae, and solar panels that respond significantly to the 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 acoustic impingement and mechanically transmitted random vibration.

4.4.1.1. **[PVTR 15]** All hardware **shall** be assessed for sensitivity to the acoustic environment.

4.4.1.2. **[PVTR 16]** Acoustic testing **shall** be performed on all hardware that is considered susceptible to the acoustic environment.

4.4.1.3. **[PVTR 17]** All payload structures and components requiring acoustic testing **shall** be subjected to broadband reverberant field or direct field acoustic testing.

The recommended method for performing acoustic testing is with a reverberant chamber test. An alternative is to perform a direct field acoustic test. Unlike reverberant testing, well-developed industry standard guidelines do not exist for direct field acoustic testing. Direct field acoustic testing is performed based on a limited knowledge of the acoustic field generated by the speakers, and ad hoc approaches are implemented in order to obtain the desired sound field. Substantial information and guidelines on implementing this state-of-the-art testing method may be found in NASA-HDBK-7010, Direct Field Acoustic Testing (DFAT).

4.4.1.4. **[PVTR 18]** Hardware/components that are mounted via vibration isolators **shall** be reviewed as candidates for acoustic testing on a case-by-case basis.

[Rationale: Vibration isolators attenuate high-frequency mechanical vibration from the source. Thus, the enveloping random vibration environment for any isolated components may come from direct acoustic impingement, even if such hardware is not usually deemed susceptible to acoustics. Therefore, assessment of the overall dynamic environment response is needed. A test program should be implemented that also satisfies the minimum workmanship criteria in section 4.3.3.]

4.4.1.5. **[PVTR 19]** Acoustic testing **shall** be performed by controlling the SPLs (dB ref: 20 μPa) in 1/3-oct bands over the specified frequency range.

If desired, the testing facility could use a higher band (1/6-oct, 1/12-oct, etc.) control system which would effectively meet and exceed the requirement. It is recommended that the 1/n octave band analysis filters conform to ANSI S1.11 and/or IEC 61260 standards. These international standards define the performance tolerances for fractional-octave filters that ensure accurate spectral representation and consistency across test labs.

4.4.1.6. **[PVTR 20]** The acoustical random noise source **shall** have an approximately normal time domain amplitude distribution.

4.4.1.7. **[PVTR 21]** The sound pressure spectrum **shall** be computed over a time duration that provides linearly weighted moving average SPLs within the test tolerances at all frequencies.

At lower frequencies, this is dependent on the acoustic chamber used and, in some cases, may be a best effort approach. Recommendation is to compute a linearly weighted average SPL.

4.4.1.8. **[PVTR 22]** Test levels **shall** be determined using the methods described in sections 4.3.1 and 4.3.2, and the test tolerances to be followed are described in section 4.4.4.

4.4.1.9. **[PVTR 23]** 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 the 50 Hz center frequency, relative to the empty chamber.

For reverberant chamber testing, the chamber volume 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 suspension system resonance.

4.4.1.10. **[PVTR 24]** The direct field acoustic 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.

Refer to NASA-HDBK-7010 for recommended guidelines for conducting direct field acoustic testing.

4.4.1.11. **[PVTR 25]** The microphones **shall** be positioned around the test chamber and direct field acoustic testing volume at sufficient distance from all surfaces.

[Rationale: This will avoid affecting the measurements by localized sound field effects near surfaces due to scattering, absorption, or reflections.]

A distance from any surface of at least 1/4 of the wavelength of the lowest frequency of interest is recommended.

4.4.1.12. **[PVTR 26]** In facilities where this distance cannot be achieved, the control microphones **shall** be located in positions to be least affected by surface effects.

4.4.1.13. **[PVTR 27]** The acoustic standing waves and structural modal coupling in reverberant field or direct field acoustic 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/direct field acoustic test 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 wave pressure excitation.

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

d. Instrument the chamber/direct field acoustic test 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/direct field acoustic test 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.

4.4.1.14. **[PVTR 28]** 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 is recommended for reverberant acoustic testing. The minimum number of control microphones recommended for direct field acoustic testing is 16. 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.

4.4.1.15. **[PVTR 29]** With the specimen in the test chamber or direct field acoustic test volume, the acoustic spectrum **shall** be shaped at a level which is no greater than -12 dB of the full level specification.

4.4.1.16. **[PVTR 30]** 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 direct field acoustic test volume, a dummy specimen may be positioned in the test chamber or direct field acoustic test 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 -12 dB of the full level specification.*

4.4.2. Random Vibration Tests

Random vibration testing is generally required for electrical, electronic, mechanical, 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 vibroacoustic environment. Exceptions are large area-to-weight structures such as solar arrays, which may be subjected to acoustic testing in lieu of random vibration, and hardware not practical to vibrate at the component level such as primary structures (vehicle skin), electrical cabling, plumbing lines, blankets, etc., that may be deferred to the system-level vibration or acoustic test. However, it is recommended during component and subsystem-level vibration testing to include their connectors and/or a representative amount of unsupported cable in order to provide proper inertial loading of the connections. This helps to ensure connector failures do not occur during the subsystem-level (or higher-level assembly) vibration or acoustic testing where they may adversely impact schedule and cost.

Random vibration testing over the frequency range of 20 – 2000 Hz may be an alternative to the system-level sine vibration test requirements of NASA-STD-7002, Payload Test Requirements (refer to "Cassini Spacecraft Force Limited Vibration Test", see APPENDIX B: REFERENCES AND BACKGROUND*).*

4.4.2.1. **[PVTR 31]** All hardware **shall** be assessed for susceptibility to mechanically transmitted random vibration due to the vibroacoustic environment.

4.4.2.2. **[PVTR 32]** Random vibration testing **shall** be performed on all hardware that is considered susceptible to mechanically transmitted random vibration due to the vibroacoustic environment.

4.4.2.3. **[PVTR 33]** 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 acoustic environment.

4.4.2.4. **[PVTR 34]** The test specimen **shall** be subjected to random vibration with a normal amplitude distribution in each of three orthogonal axes.

4.4.2.5. **[PVTR 35]** 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.

4.4.2.6. **[PVTR 36]** The spectrum **shall** be within the test tolerance specified in section 4.4.4.

4.4.2.7. **[PVTR 37]** Monitoring accelerometers **shall** be mounted next to the test specimen to accurately measure its testing environment and verify the test spectrum of the control accelerometers is appropriately modified, while taking into account facility health.

For vibration testing, two or more control accelerometers should be mounted at the hardware attachment points to the test fixture. The control accelerometers should be mounted at dispersed locations to prevent them from being at nodes of the same mode.

4.4.2.8. **[PVTR 38]** 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.

4.4.2.9. **[PVTR 39]** The test fixture **shall** be subjected to a bare resonance survey prior to the start of testing.

In order to obtain insight into modal characteristics of the test setup, it is recommended to perform a survey with a mass simulator of the test specimen mounted to the test fixture. The specified criteria for the resonance survey should be relevant to the test specification.

4.4.2.10. **[PVTR 40]** The fixture (in test configuration) **shall** be evaluated for resonances within the test frequency range.

If practical, the fixture should have no resonances within the test frequency range. Coupling between the test article and fixture should be avoided.

4.4.2.11. **[PVTR 41]** The test specimen **shall** be mounted to the fixture via its flight or flight-equivalent mounting attachments.

The use of a slip table or expander head to adapt a fixture to a shaker may result in modes of the test specimen differing significantly from modes of the flight configuration. Caution should be taken to prevent possible under-testing or over-testing due to modal coupling of a slip table or expander head with the test article.

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 hard-mounted 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.*

4.4.3. Test Duration

4.4.3.1. [PVTR 42] The durations for the tests described in sections 4.4.1 (Acoustic Tests) and 4.4.2 (Random Vibration Tests) **shall** be as defined in the following subsections.

Note: There can be other situations (e.g., retesting of reflight hardware, inclusion of qual hardware in higher levels of assembly, reentry) where the qualification durations defined below are not adequate to fully qualify the hardware for the entire service life. Test conditions will be defined by applying test tailoring (see section 4.4.6).

4.4.3.2. Qualification Test Duration

4.4.3.2.1. [PVTR 43] The vibroacoustic qualification test durations **shall** be a minimum 2 minutes for the acoustic test and 2 minutes in each of the 3 orthogonal axes for the vibration test.

4.4.3.2.2. [PVTR 44] If the flight hardware is to be reflown N times, the corresponding qualification test durations **shall** be a minimum 2 + 0.5N minutes.

Note: The value N, number of reflights, is expected to be a zero-based whole number.

4.4.3.3. Protoflight Test Duration

4.4.3.3.1. [PVTR 45] 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.

4.4.3.4. Acceptance Test Duration

4.4.3.4.1. [PVTR 46] The vibroacoustic acceptance test durations **shall** be a minimum 1 minute for an acoustic test and 1 minute in each of the 3 orthogonal axes for a vibration test.

4.4.4. Test Control Tolerances

4.4.4.1. [PVTR 47] The acceptable tolerances for vibroacoustic testing **shall** be as follows:

a. Vibration

(1) Composite rms acceleration .... ±10%

(2) Acceleration spectral density. ....±3 dB

i. (25 Hz or less frequency bandwidth resolution)

(3) Frequency.. ±5%

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

b. Acoustic

(1) Individual 1/3-oct band SPLs (50 to 3150 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 3150 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.

4.4.5. Test Configuration

4.4.5.1. **[PVTR 48]** A satisfactory verification test program **shall** adhere to the following test configuration methods.

Note: 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 4.3.3, workmanship testing should be conducted at lower levels of assembly (e.g., down to the board level, if necessary).

4.4.5.1.1. **[PVTR 49]** During testing, the mechanical configuration of the test item **shall** be in a liftoff operational mode (excluding explosive devices during vibration tests for systems that include pyrotechnics).

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.

4.4.5.1.2. **[PVTR 50]** The electrical operating mode **shall** be in accordance with the test plan.

4.4.5.1.3. **[PVTR 51]** As a minimum requirement, the liftoff electrical condition **shall** be applied and monitored.

4.4.5.1.4. **[PVTR 52]** In mating the test article to the test fixture, a flight-type mounting (including vibration isolators, if part of the design), fasteners, torque values, and lubricants **shall** be used.

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

4.4.5.1.5. **[PVTR 53]** Components that are normally sealed **shall** be pressurized during the test to their pre-launch pressure.

4.4.5.1.6. **[PVTR 54]** 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.

4.4.5.2. **[PVTR 55]** Random vibration testing **shall** precede thermal-vacuum testing.

4.4.6. Test Tailoring Methods

This Standard serves as a baseline that provides enough flexibility to allow tailoring to the needs of non-baseline situations.

4.4.6.1. **[PVTR 56]** All requirements of this Standard **shall** be evaluated for each spacecraft application.

For example, if the flight hardware will be subjected to component and additional system level tests, multiple acceptance tests, or flight equivalent duration that exceeds 7.5 seconds, the specified durations for qualification testing may not cover the full service life.

4.4.6.2. **[PVTR 57]** 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.

Another example would be cases where there is concern that exposing the hardware to additional testing at MEFL will pose a risk of fatigue damage. 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 4.3.3.

4.4.6.3. **[PVTR 58]** 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 4.4.2.

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. Stowage.

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.

4.5. Dynamic Data Acquisition and Analysis

Additional information about dynamic data acquisition and analysis of vibroacoustic data are included in NASA-HDBK-7005.

4.5.1. **[PVTR 59]** 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.

4.5.2. **[PVTR 60]** The minimum statistical basis to be used for defining MEFL **shall** be P95/C50 assuming a log-normal distribution of the data. *The P95/C50 level is defined as enveloping 95 percent of the data with a 50 percent confidence level.*

The methodology for calculating the P95/C50 level based on measured flight data is described in Appendix C.1.1 Statistical Standards.

If fewer than three data samples are available, then the P95/C50 level may be calculated based on the methods presented in Appendix C.1.1 Statistical Standards *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/C50 normal* *tolerance limit is given by Equation 1 below:*

$$P95/C50 = X_m + KS_x = X_m + 1.65 * 3dB = X_m + 5dB \qquad \text{(Eq. 1)}$$

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.*

4.5.3. **[PVTR 61]** The maximum bandwidths to be used for deriving the enveloped MEFL spectrum **shall** be as defined below:

a. Acoustic SPL: 1/3 oct bands.

b. Random Vibration Power Spectral Density (PSD): 1/6 oct bands.

4.5.4. **[PVTR 62]** Random vibration levels derived using vibroacoustic prediction techniques such as statistical energy analysis (SEA) and boundary element analysis (BEA) **shall** meet the bandwidth requirements of section 4.5.3, and the analysis results **shall** be scaled to account for the peak response of the hardware.

SEA results are typically calculated as 1/3 oct 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 P95/C50 random vibration environment.

Methods for vibroacoustic analysis are discussed in more detail in APPENDIX C: METHODS FOR VIBROACOUSTIC ANALYSES.

4.5.5. **[PVTR 63]** Ground test operations and transportation vibroacoustic levels **shall** be controlled so that levels produced by these events do not exceed the MEFLs.

4.5.6. **[PVTR 64]** 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: REQUIREMENTS IDENTIFICATION MATRIX

A.1 PURPOSE

Due to the complexity and uniqueness of space flight, it is unlikely that all the requirements in a Standard will apply. The Requirements Identification Matrix below contains this Standard's technical authority requirements and may be used by programs and projects to indicate requirements that are applicable or not applicable. Enter "Yes" in the "Applicable" column if the requirement is applicable to the program or project or "No" if the requirement is not applicable to the program or project. The "Comments" column may be used to provide specific instructions on how to apply the requirement, specify proposed tailoring, or provide an explanation/justification when not applicable.

A.2 REQUIREMENTS IDENTIFICATION MATRIX TABLE

Table 3—Requirements Identification Matrix

NASA-STD-7001C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.1.1	Summary of Verification Test Requirements	**[PVTR 1]** A permanent record of all payloads and environments generated using this Standard shall **be** maintained by the project's quality assurance organization.		
4.3.1.1	Qualification and Protoflight Tests	**[PVTR 2]** Acoustic qualification tests **shall** be conducted at levels that envelope flight acceptance levels plus 3 dB.		
4.3.1.2	Qualification and Protoflight Tests	**[PVTR 3]** Acoustic protoflight tests **shall** be conducted at levels that envelope MEFL plus 3 dB and minimum workmanship levels defined in section 4.3.3.		
4.3.1.3	Qualification and Protoflight Tests	**[PVTR 4]** Random vibration qualification tests **shall** be conducted at levels that envelope flight acceptance levels plus 3 dB.		
4.3.1.4	Qualification and Protoflight Tests	**[PVTR 5]** Random vibration protoflight tests **shall** be conducted at levels that envelope MEFL plus 3 dB and minimum workmanship levels defined in section 4.3.3.		
4.3.2.1	Acceptance Testing	**[PVTR 6]** Acoustic flight acceptance tests **shall** be conducted at levels that envelope MEFL and are equal to or greater than the minimum acoustic workmanship levels defined in section 4.3.3.		
4.3.2.2	Acceptance Testing	**[PVTR 7]** Random vibration flight acceptance tests **shall** be conducted at levels that envelope the MEFL and the minimum workmanship levels as defined in section 4.3.3.		

NASA-STD-7001C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.3.3.1	Workmanship	**[PVTR 8]** For components weighing less than 50 kg (110 lb), the spectrum shown in Table 2, Component Minimum Workmanship Random Vibration Test Levels, **shall** be used as a minimum vibration test specification. **Table 2—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 grms		
4.3.3.2	Workmanship	**[PVTR 9]** The component **shall** be subjected to the minimum workmanship random vibration test level along each of three orthogonal axes for the appropriate duration as specified in section 4.4.3.		
4.3.3.3	Workmanship	**[PVTR 10]** Components **shall** be hard-mounted to the shaker.		
4.3.3.4	Workmanship	**[PVTR 11]** Workmanship acoustic testing **shall** be performed for all hardware levels of assembly described in section 4.4.1.		
4.3.3.5	Workmanship	**[PVTR 12]** The minimum workmanship acoustic test level **shall** be 138 dB overall sound pressure level (OASPL), via one of the following methods: Method 1: The minimum acoustic workmanship level is specified in Table 8.11 of NASA-HDBK-7005, Dynamic Environmental Criteria. Method 2: The minimum acoustic workmanship level of 138 dB OASPL may alternatively be achieved by uniformly scaling the MEFL spectrum.		
4.3.4.1	Acoustic Fill Effect	**[PVTR 13]** For payloads which exhibit extensive volumetric physical fill, the acoustic environment **shall** be adjusted to account for the fill effect of the payload within the launch vehicle fairing.		
4.3.4.2	Acoustic Fill Effect	**[PVTR 14]** If the payload is highly unsymmetrical or has discrete structures or appendages, then engineering judgment **shall** be utilized in applying the fill effect.		
4.4.1.1	Acoustic Tests	**[PVTR 15]** All hardware **shall** be assessed for sensitivity to the acoustic environment.		
4.4.1.2	Acoustic Tests	**[PVTR 16]** Acoustic testing **shall** be performed on all hardware that is considered susceptible to the acoustic environment.		
4.4.1.3	Acoustic Tests	**[PVTR 17]** All payload structures and components requiring acoustic testing **shall** be subjected to broadband reverberant field or direct field acoustic testing.		
4.4.1.4	Acoustic Tests	**[PVTR 18]** Hardware/components that are mounted via vibration isolators **shall** be reviewed as candidates for acoustic testing on a case-by-case basis.		

NASA-STD-7001C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.4.1.5	Acoustic Tests	**[PVTR 19]** Acoustic testing **shall** be performed by controlling the SPLs (dB ref: 20 μPa) in 1/3-oct bands over the specified frequency range.		
4.4.1.6	Acoustic Tests	**[PVTR 20]** The acoustical random noise source **shall** have an approximately normal time domain amplitude distribution.		
4.4.1.7	Acoustic Tests	**[PVTR 21]** The sound pressure spectrum **shall** be computed over a time duration that provides linearly weighted moving average SPLs within the test tolerances at all frequencies.		
4.4.1.8	Acoustic Tests	**[PVTR 22]** Test levels **shall** be determined using the methods described in sections 4.3.1 and 4.3.2, and the test tolerances to be followed are described in section 4.4.4.		
4.4.1.9	Acoustic Tests	**[PVTR 23]** 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 the 50 Hz center frequency, relative to the empty chamber.		
4.4.1.10	Acoustic Tests	**[PVTR 24]** The direct field acoustic 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.		
4.4.1.11	Acoustic Tests	**[PVTR 25]** The microphones **shall** be positioned around the test chamber and direct field acoustic testing volume at sufficient distance from all surfaces.		
4.4.1.12	Acoustic Tests	**[PVTR 26]** In facilities where this distance cannot be achieved, the control **microphones** shall be located in positions to be least affected by surface effects.		
4.4.1.13	Acoustic Tests	**[PVTR 27]** The acoustic standing waves and structural modal coupling in reverberant field or direct field acoustic testing **shall** be assessed and steps taken to minimize the impact of such coupling on the health of the test specimen.		
4.4.1.14	Acoustic Tests	**[PVTR 28]** 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.		
4.4.1.15	Acoustic Tests	**[PVTR 29]** With the specimen in the test chamber or direct field acoustic test volume, the acoustic spectrum **shall** be shaped at a level which is no greater than -12 dB of the full level specification.		
4.4.1.16	Acoustic Tests	**[PVTR 30]** The time required to shape the spectrum **shall** be minimized to avoid possible fatigue of the test specimen.		
4.4.2.1	Random Vibration Tests	**[PVTR 31]** All hardware **shall** be assessed for susceptibility to mechanically transmitted random vibration due to the vibroacoustic environment.		

NASA-STD-7001C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.4.2.2	Random Vibration Tests	**[PVTR 32]** Random vibration testing **shall** be performed on all hardware that is considered susceptible to mechanically transmitted random vibration due to the vibroacoustic environment.		
4.4.2.3	Random Vibration Tests	**[PVTR 33]** 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 acoustic environment.		
4.4.2.4	Random Vibration Tests	**[PVTR 34]** The test specimen **shall** be subjected to random vibration with a normal amplitude distribution in each of three orthogonal axes.		
4.4.2.5	Random Vibration Tests	**[PVTR 35]** Random vibration testing **shall** be performed by controlling the acceleration spectral density (g2/Hz) in 25 Hz or less frequency bandwidths over the frequency range from 20 to 2000 Hz.		
4.4.2.6	Random Vibration Tests	**[PVTR 36]** The spectrum **shall** be within the test tolerance specified in section 4.4.4.		
4.4.2.7	Random Vibration Tests	**[PVTR 37]** Monitoring accelerometers **shall** be mounted next to the test specimen to accurately measure its testing environment and verify the test spectrum of the control accelerometers is appropriately modified, while taking into account facility health.		
4.4.2.8	Random Vibration Tests	**[PVTR 38]** 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.		
4.4.2.9	Random Vibration Tests	**[PVTR 39]** The test fixture **shall** be subjected to a bare resonance survey prior to the start of testing.		
4.4.2.10	Random Vibration Tests	**[PVTR 40]** The fixture (in test configuration) **shall** be evaluated for resonances within the test frequency range.		
4.4.2.11	Random Vibration Tests	**[PVTR 41]** The test specimen **shall** be mounted to the fixture via its flight or flight-equivalent mounting attachments.		
4.4.3.1	Test Duration	**[PVTR 42]** The durations for the tests described in sections 4.4.1 (Acoustic Tests) and 4.4.2 (Random Vibration Tests) **shall** be as defined in the following subsections.		
4.4.3.2.1	Qualification Test Duration	**[PVTR 43]** The vibroacoustic qualification test durations **shall** be a minimum 2 minutes for the acoustic test and 2 minutes in each of the 3 orthogonal axes for the vibration test.		
4.4.3.2.2	Qualification Test Duration	**[PVTR 44]** If the flight hardware is to be reflown N times, the corresponding qualification test durations **shall** be a minimum 2 + 0.5N minutes.		
4.4.3.3.1	Protoflight Test Duration	**[PVTR 45]** 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.		
4.4.3.4.1	Acceptance Test Duration	**[PVTR 46]** The vibroacoustic acceptance test durations **shall** be a minimum 1 minute for an acoustic test and 1 minute in each of the 3 orthogonal axes for a vibration test.		

NASA-STD-7001C				
Section	Description	Requirement in this Standard	Applicable (Enter Yes or No)	Comments
4.4.4.1	Test Control Tolerances	**[PVTR 47]** The acceptable tolerances for vibroacoustic testing **shall** be as follows: a. Vibration (1) Composite rms acceleration .... ±10% (2) Acceleration spectral density. ....±3 dB (3) Frequency... ±5% i. (25 Hz or less frequency bandwidth resolution) (4) Test duration ....+10%, -0% b. Acoustic (1) Individual 1/3-oct band SPLs (50 to 3150 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 3150 Hz.		
4.4.5.1	Test Configuration	**[PVTR 48]** A satisfactory verification test program **shall** adhere to the following test configuration methods.		
4.4.5.1.1	Test Configuration	**[PVTR 49]** During testing, the mechanical configuration of the test item **shall** be in a liftoff operational mode (excluding explosive devices during vibration tests for systems that include pyrotechnics).		
4.4.5.1.2	Test Configuration	**[PVTR 50]** The electrical operating mode **shall** be in accordance with the test plan.		
4.4.5.1.3	Test Configuration	**[PVTR 51]** As a minimum requirement, the liftoff electrical condition **shall** be applied and monitored.		
4.4.5.1.4	Test Configuration	**[PVTR 52]** In mating the test article to the test fixture, a flight-type mounting (including vibration isolators, if part of the design), fasteners, torque values, and lubricants **shall** be used.		
4.4.5.1.5	Test Configuration	**[PVTR 53]** Components that are normally sealed **shall** be pressurized during the test to their pre-launch pressure.		
4.4.5.1.6	Test Configuration	**[PVTR 54]** 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.		
4.4.5.2	Test Configuration	**[PVTR 55]** Random vibration testing **shall** precede thermal-vacuum testing.		
4.4.6.1	Test Tailoring Methods	**[PVTR 56]** All requirements of this Standard **shall** be evaluated for each spacecraft application.		
4.4.6.2	Test Tailoring Methods	**[PVTR 57]** Any specified tailoring **shall** be accompanied by a statement of the technical rationale for the tailoring.		
4.4.6.3	Test Tailoring Methods	**[PVTR 58]** The logic used to develop a specific notching rationale **shall** be validated.		

NASA-STD-7001C				
Section	**Description**	**Requirement in this Standard**	**Applicable (Enter Yes or No)**	**Comments**
4.5.1	Dynamic Data Acquisition and Analysis	**[PVTR 59]** 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		
4.5.2	Dynamic Data Acquisition and Analysis	**[PVTR 60]** The minimum statistical basis to be used for defining MEFL **shall** be P95/C50 assuming a log-normal distribution of the data. *The P95/C50 level is defined as enveloping 95 percent of the data with a 50 percent confidence level.*		
4.5.3	Dynamic Data Acquisition and Analysis	**[PVTR 61]** The maximum bandwidths to be used for deriving the enveloped MEFL spectrum **shall** be as defined below: a. Acoustic SPL: 1/3 oct bands. b. Random Vibration Power Spectral Density (PSD): 1/6 oct bands.		
4.5.4	Dynamic Data Acquisition and Analysis	**[PVTR 62]** Random vibration levels derived using vibroacoustic prediction techniques such as statistical energy analysis (SEA) and boundary element analysis (BEA) **shall** meet the bandwidth requirements of section 4.5.3, and the analysis results **shall** be scaled to account for the peak response of the hardware.		
4.5.5	Dynamic Data Acquisition and Analysis	**[PVTR 63]** Ground test operations and transportation vibroacoustic levels **shall** be controlled so that levels produced by these events do not exceed the MEFLs.		
4.5.6	Dynamic Data Acquisition and Analysis	**[PVTR 64]** 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 B: REFERENCES AND BACKGROUND

B.1 PURPOSE

This Appendix provides information of a general or explanatory nature but does not contain requirements. The latest issuances of reference documents apply unless specific versions are designated. Access reference documents at https://standards.nasa.gov or obtain documents directly from the Standards Developing Body, other document distributors, information provided or linked, or by contacting the office of primary responsibility designee for this Standard.

B.2 REFERENCE DOCUMENTS

NPR 8705.4**,** Risk Classification for NASA Payloads

NASA-STD-5002**,** Load Analyses of Spacecraft and Payloads

NASA-STD-7002, Payload Test Requirements

NASA-HDBK-7004, Force Limited Vibration Testing

NASA-HDBK-7005, Dynamic Environmental Criteria

NASA-HDBK-7010, Direct Field Acoustic Testing (DFAT)

NASA-CR-173472, NASA Flight Electronics Environmental Stress Screening Survey, E.J. Marian, Washington, DC, December 1983

NASA-TM-106688, NASA LeRC's Acoustic Fill Effect Test Program and Results, W. Hughes, M. McNelis, J. Manning, October 1994

NASA-TN-2158, Statistical Techniques for Describing Localized Vibratory Environments of Rocket Vehicles, Robert E. Barrett

Cassini Spacecraft Force Limited Vibration Test, K. Y. Chang and Terry D. Scharton, Sound and Vibration Magazine, March 1998, pp. 16-20

Force Specifications for Extremal Dual Controlled Vibration Tests, Terry Scharton, 61st Shock and Vibration Symposium, Los Angeles, CA, October 1990
Statistical Energy Analysis of Dynamical Systems: Theory and Applications, by R.H. Lyon, MIT Press, Cambridge, MA, 1975

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

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

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

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

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

IEST-RP-DTE012.2, 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

Boundary Element Method (BEM) Data Analysis Processing: Comparison of Analysis Bandwidth Reduction Methods, Spacecraft & Launch Vehicle Dynamic Environments Workshop 2010, Larko, McNelis, & Gardner, 2010

B.3 KEY WORD LISTING

a. Acceptance test

b. Acoustic

c. Qualification test

d. Random vibration

e. Vibration

f. Vibroacoustic

B.4 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 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 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 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 Engineering and Safety 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 C: METHODS FOR VIBROACOUSTIC ANALYSES

C.1 DATA ANALYSIS

C.1.1 Statistical Standards

The vibroacoustic test levels are a function of the MEFL, as specified in sections 4.3.1 and 4.3.2, and are based upon statistically estimated spectral levels. A P95/C50 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:

$$X_{95/50}(f) = \bar{X} + KS_x \qquad \text{(Eq. 2)}$$

where $X_{95/50}$ is the percentile level corresponding to the $P_{95/C50}$ level, $\bar{X}$, 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 $1\ \mu Pa^2$ 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 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):

$$X_{95/50}(f), in\ dB = \bar{X} + CF(KS_x) \qquad \text{(Eq. 3)}$$

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 $\bar{X}$, in dBs, would become equal to 10 CF $(K\ S_x)$ and the following modified expression would result:

$$Y_{95/50}(f), \text{in}\ \frac{g^2}{Hz} = 10^{(\bar{X}+CF(kS_x))} \qquad \text{(Eq. 4)}$$

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

$\log_{10y}(y)$.

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 $P_{95/C50}$ level.

C.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. Judgement may be necessary when there are co-payloads in the same volume.

2. Calculate the empty fairing/enclosure 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 volume, Vol_{ratio}.

$$Vol_{ratio} = \frac{Vol_{payload}}{Vol_{empty}} \qquad \text{(Eq. 5)}$$

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

5. Use Equation 6 below to calculate the acoustic fill effect in dB, as a function of frequency (f).

$$\text{Fill Factor (dB)} = 10\log_{10}\left[\frac{\left(1+\frac{c_a}{2f\,H_{gap}}\right)}{1+\left(\frac{c_a}{2f\,H_{gap}}\right)(1-Vol_{ratio})}\right] \qquad \text{(Eq. 6)}$$

where:

c_a is the speed of sound in air (typically 344.4 meters/second (1130 feet/second) at 68 degrees F).

f is the 1/3-oct band center frequency (Hz).

H_{gap} is the average gap distance between the payload and the fairing/ enclosure wall.

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

6. Determine the acoustic levels for the empty fairing/ enclosure. 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/ enclosure volume.

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

Figure 1, Fill Factor Design Chart, 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/ enclosure volume, and the increase due to the fill effect should be applied to the acoustic level for the empty fairing/ enclosure with any baseline fill effects removed.

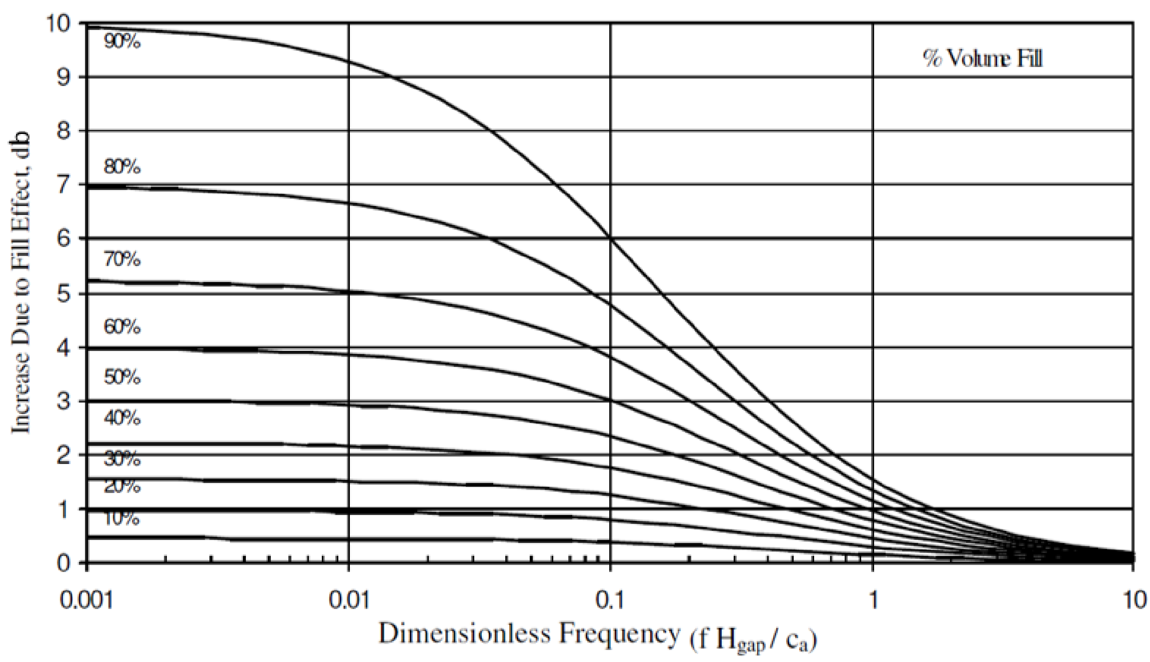

Figure 1—Fill Factor Design Chart

Fill effects greater than those predicted are possible in individual 1/3-oct bands at low frequencies. These exceedances are due to unique payload geometries that cause shifting of acoustic modes (refer to NASA-TM-106688, 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/ enclosure combination, caution should be used when interpreting flight data fill effects and applying them to another payload and fairing/ enclosure combination which is geometrically dissimilar.

C.1.3 Mass Attenuation of the Minimum Workmanship Vibration Level

The plateau acceleration spectral density (ASD) level 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 log10(W/50)	10 log10(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 lb, the workmanship test spectrum is 0.01 g^2/Hz from 20 to 2000 Hz with an overall level of 4.4 grms. The mass-attenuated workmanship spectrum is shown in Figure 2, Mass Attenuated Workmanship Vibration Spectrum.

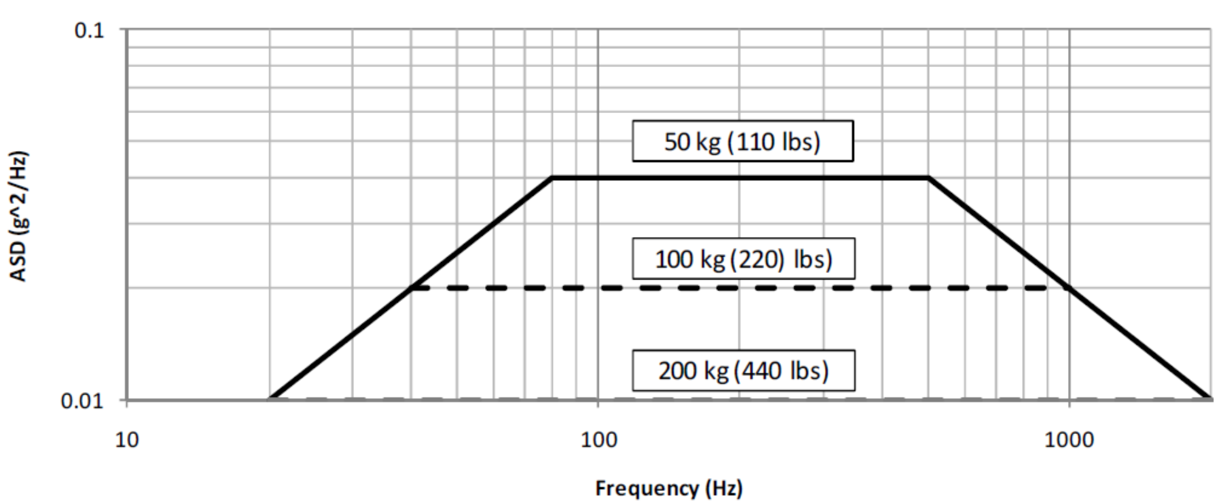

Figure 2—Mass Attenuated Workmanship Vibration Spectrum

C.2 ANALYSIS METHODS

C.2.1 Statistical Energy Analysis (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.

The SEA modeling approach is different than FEA. It is a statistical method, as opposed to the deterministic nature of FEA. Instead of subdividing the structure into discrete elements of only a few inches as in FEA, the SEA analyst strives to subdivide into large statistical subsystems, perhaps per physical panel. In FEA, each slight change, such as an added composite panel ply, may warrant a new property. But in SEA, the analyst must avoid such small subsystems, and either use an average panel property, or the dominant acreage property. Additionally, SEA omits small components, as they do not affect panel vibration significantly at mid-high frequencies and are not easily modeled with available SEA subsystem types (plates and beams). As such, SEA models are not expected to match FEM mass. SEA predicts the statistical ensemble response of each subsystem, rather than the response at discrete points.

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. Even though SEA modeling does not require the detailed structural modeling that FEA, BEA, and hybrid do, the modeling time for large complex structures can be large. SEA is both less computationally expensive than the other methods and allows for parameter redesign analysis.

Traditionally, low frequency FEM and BEM methods have been used to predict low-mid frequency response and still remain the most accurate methods for these frequencies. However, modern SEA codes can estimate a response variance in addition to the mean, such that SEA may be used in low frequencies and low modal densities. For these cases, the confidence interval will be larger, resulting in a conservative maximum expected environment. This is particularly useful for retaining acoustic cavities as SEA subsystems, as structure would still benefit from FEA methods in order to include their boundary conditions. SEA is also not limited to broadband analysis, as is typically performed (1/3 octave band analysis is common). For the case of increasingly more narrowband analysis in SEA, the confidence interval will grow. It is important to note that SEA cannot be used below the first mode of each subsystem. In addition, SEA provides results that represent the spatially averaged spectral response of the structure. If localized response quantities (acceleration, displacement, force, or stress) are desired, these must be estimated from the SEA results or may require that alternate analysis methods be used.

SEA has been used to solve a variety of aerospace problems There are a number of commercial codes available to perform SEA.

C.2.2 Finite Element Analysis (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).

FEA is beginning to appear in vibroacoustic analyses more and more as capability improvements and availability of computer resources make using larger, more refined models less burdensome. There is also a degree of complexity involved when representing acoustic field-type excitations for the finite element (FE) models, which for most aerospace applications is induced by aeroacoustic rocket engine noise and aerodynamic flow.

The suitability of FE models proposed for vibroacoustics estimates should always be evaluated over the frequency range of interest. Guidelines for model suitability are as follows:

1. Focus on objectives and determine the limitations of proposed models:

    a. What frequency range of interest is important for this assessment?

    b. Use models appropriate to the task focus and identified frequency range.

2. Some FEM modeling approaches impose limitations on suitability of models in mid- to high-frequency range:

    a. Inadequate Mesh Density.

        i. The mesh density of pressure field excited panels should be fine enough to provide at least 4–6 elements per fluid wavelength for the forcing function.

ii. The mesh density for the FEM elastic structures should provide at least 6 elements per wavelength of the structural bending shapes. Structural bending wavelengths are not as simple to compute as fluid wavelengths. However, modern vibroacoustic codes can compute this from an SEA subsystem. Alternatively, observing smooth curves in the highest frequency mode shapes of the FEM is an acceptable check. The analyst should provide some form of verification that the structural FEM mesh density has met this metric.

b. Overuse of lumped mass and multi-point constraints (MPCs) to represent elastic multi-degree-of-freedom (MDOF) subsystems.

i. Simplifications that represent MDOF subsystems as a lump mass idealization limit the frequency range of suitability.

ii. As an example, an avionics box assembled with structural cover, front, back, and side walls, bottom, and circuit boards is an MDOF. Each of the walls and circuit boards of the box have resonant modes. At low frequencies, the assumption that the box is a rigid, lumped mass with inertial moments is a reasonable approximation. As we approach the range where the box has its own resonant modes, that assumption breaks down and is no longer suitable.

iii. The suitable range for models using lumped mass assumptions should be assessed. Ideally, the MDOF modeling would be required when the frequency range where subsystems have their own resonant modes.

iv. The most recognizable effect of overuse of lumped mass and rigid element simplifications for MDOF (using them beyond the appropriate frequency range) is the inability of the simulation to represent the apparent mass effects at reaction locations that should be demonstrated for real physical systems. This can result in an over-conservative estimate of interaction with the backup structures in the mid- to high-frequency range. This results from false estimates of integrated response modes that associate too much effective weight at the reaction points.

v. Extending the frequency range of the model solution usually requires refinement of the model so that the MDOF modes are represented by elastic elements with distributed mass.

Using more than one modeling approach to represent the entire frequency range of interest for vibroacoustics is a best practice. It is usually a poor strategy to attempt to make one system model suffice for all environments and interface loads assessments. Breakout FEA models of smaller subsystems with more refined mesh details are sometimes employed to answer response estimate questions that the larger system model was not suited to achieve.

FE/SEA hybrid techniques and SEA (section C.2.1 Statistical Energy Analysis (SEA)) approaches are available to extend the frequency range and provide appropriate response estimates in the mid- to high-frequency range, respectively.

FE/SEA hybrid models that combine structural SEA panels with adjacent FE panels should not be used to provide vibration response estimates in the low frequency bands. The response in low frequency bands is very dependent on boundary conditions, which the SEA portion of the hybrid model is not suited to represent. Although the SEA methodology is powerful at lower frequencies (typically below a few hundred Hz), SEA's underlying assumptions regarding modal density, modal equivalence, and boundary conditions result in predictions that are invalid. But FEA, and Boundary Element Analysis (BEA, Section C.2.3 Boundary Element Analysis (BEA)), techniques provide alternative methodologies for making vibroacoustic predictions in the low frequency range.

Two different types of FEA methods exist for predicting acoustic response:

1. 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 requires adequately fine mesh sizes to accurately represent the structure-fluid interaction.

    a. Six elements per fluid wavelength are recommended to represent the air in cavities with discontinuities and complicated geometries such as corners and edges.

    b. An example of a cavity without such complication might be a spherical pressure vessel.

    c. The acoustic FEM modeling technique is primarily used for interior noise studies, modal analysis, and damping treatments.

    d. When modeling an acoustic cavity, it is important to adjust the fluid properties to match the flight event of interest; significant differences in fluid properties may exist between liftoff and an ascent case. For acoustic FEM cavities, any change in fluid properties requires the cavity modes to be solved again.

2. 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.

    a. 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.

    b. 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.

c. 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.

The BEA method may be easier to implement reliably for response of sub-elements where edge effects and double-sided pressure loading on exposed surfaces are important to the estimate.

FEA techniques, as opposed to SEA, utilize discrete modes. It is important to capture this modal behavior. Therefore, it is recommended to run FEA in narrowband. The frequency spacing should be less than the half power bandwidth, also called the modal bandwidth. Reference *Larko* provides a table of nth octave bandwidths appropriate to capture peaks within 3dB, based on structural damping. Narrowband results can then be down-converted to third octave band if desired. This also applies to other low-frequency methods such as BEA.

C.2.3 Boundary Element Analysis (BEA)

BEA is a deterministic approach, typically solved in the frequency domain, that can be used to predict acoustic-induced structural vibration, the sound field in interior and exterior spaces, and the sound radiated by vibrating structures. The BEA method models the structure with finite elements discussed in section C.2.2 Finite Element Analysis (FEA) 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 C.2.1 Statistical Energy Analysis (SEA), 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. Many commercial BEA codes are available.

Unlike finite element-based acoustic cavity models, which require a volumetric mesh of the fluid, BEA fluids require only a mesh of the surface of the cavity (or exterior fluid). BEA uses the boundaries to compute the acoustic field anywhere within the cavity (or exterior). However, care must be taken when using BEA. It is highly sensitive to unintended slits. It is important to ensure there are no free edges in the fluid boundary mesh if the intent is to model a sealed cavity, or sealed wrap over the spacecraft exterior. This is sometimes called a watertight mesh. Most spacecraft FEMs have free edges at interfaces joined by CBUSH or RBE elements, but there is no physical gap in the hardware. Thus, the BEA analyst will usually need to seal over the free edges. However, if there are slit openings in the hardware, these should be modeled.

BEA is a powerful method for modeling an external acoustic field impinging on a spacecraft. In the low-to-mid frequencies, it is more accurate than surface loads. BEA excitation is particularly recommended for spacecraft with many unbaffled surfaces, such as stand-off radiators and antennas, as these features cause the assumptions of surface pressure loading to become overly conservative.

C.2.4 Complete Analytical Tools

The analyst may need to combine different methods of analysis discussed in sections C.2.1 Statistical Energy Analysis (SEA) — C.2.3 Boundary Element Analysis (BEA) 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 used more widely but it still awaits verification using experimental data. In general, BEA and acoustic FEA techniques are applicable to the low frequency range. FEA structure models may be extended to mid-frequency range by refinement of model mesh and converting lump-mass simplifications to explicit elastic model representations (modeling smaller subsystems in more detail as breakout models may be appropriate for certain response estimates). The hybrid SEA/FEA methods are applicable to the mid-frequency range (but not the extreme low frequency), and SEA is appropriate for the high-frequency region. As mentioned in section C.2.2 Finite Element Analysis (FEA), the patch method can also be used to derive structural response predictions in the low-frequency range using standard FEA techniques; but take care 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 D: VIBROACOUSTIC LOAD PREDICTIONS

D.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 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.

D.1.1 Combination of Loads

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

> **4.8.5** [LAR 45] The quasi-static, low frequency transient loads, and random vibration/acoustic limit loads shall be combined as approved by the delegated Technical Authority to determine the total load environment for liftoff.
>
> *For a component that weighs more than 500 kilograms (kg), the overall random vibration load may be assumed to be small relative to the low frequency transient load and therefore neglected. For components weighing less than 500 kg, the appropriate method of load combination will be 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 LV, 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. When the low frequency transient and random vibration environments are specified in a time-correlated manner, a time-consistent approach is also acceptable for combining the low frequency transient loads and the random vibration loads.*